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A CONCEPTUAL DESIGN STUDY OF A HOVERING SYSTEM
CONTROLLER FOR AN AUTONOMOUS UNDERWATER VEHICLE

by

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An Autonomous Underwater Vehicle (AUV) will have many operational scenarios that will include a transition from cruise to hover over a fixed position in the ocean. While hovering, the AUV must be able to balance the current induced forces - a difficult task to accomplish automatically. The magnitude of these forces induced on an example AUV have been estimated for currents from 4 m/s to 1 m/s with the incident current varying from 0° to 360° Using the estimated forces, different configurations of thrusters were investigated and the power required for different thruster configurations compared. Three thrusters (two longitudinal, one lateral) can balance the forces exactly and a unique solution was evaluated. With redundant thrusters, more economical schemes can developed using force allocation logic with "minimum norm" solutions. System horsepower requirements have been estimated and a

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A Conceptual Design Study of A Hovering System Controller For An Autonomous Underwater Vehicle

by

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requirements for the degree of

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ABSTRACT

An Autonomous Underwater Vehicle (AUV) will have many operational scenarios that will include a transition from cruise to hover over a fixed position in the ocean. While hovering, the AUV must be able to balance the current induced forces - a difficult task to accomplish automatically. The magnitude of these forces induced on an example AUV have been estimated for currents from 4 m/s to 1 m/s with the incident current varying from 0° to 360° Using the estimated forces, different configurations of thrusters were investigated and the power required for different thruster configurations compared. Three thrusters (two longitudinal, one lateral) can balance the forces exactly and a unique solution was evaluated. With redundant thrusters, more economical schemes can developed using force allocation logic with "minimum norm" solutions. System horsepower requirements have been estimated and a conceptual model based controller methodology has been proposed. The force allocation logic proposed will now allow for a smooth transition from cruise to hover mode positions.

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I. INTRODUCTION/BACKGROUND

The Navy's goal of maintaining a 600 ship Navy is rapidly coming to fruition. As the size of the Navy grows, the manning of these ships become critical. This manning shortage must be dealt with by turning to automation. Admiral Metcalfe, Deputy Chief of Naval Operations (Surface Warfare), in his letter, "Revolution at Sea-Tactics and Ship Design", stressed the importance of utilizing "innovative, free thinking engineering talent" to keep the design of surface ships in step with the technology changes in Combat Weapons Systems. The emphasis here is in automating more functions for a more efficient fighting platform. [Ref. 1]

This can easily be extended to the underwater world. In the past and continuing to the present, the use of small submarines and remotely operated vehicles (ROV) has been crucial to the success of underwater missions such as; search and rescue, ocean floor surveillance, underwater structural repair, deep sea research, recovery of sensitive or important equipment lost at sea, and a myriad of other jobs too tedious or dangerous for man.

A. CURRENT TECHNOLOGY

In this section current technology both in ROV's and AUV's will be reviewed followrd by a discussion of teh goals of this work.

1. ROV Technology

All ROVs have a common factor, a tether, or better described as, an umbilical. It is the ROV's "life line", it provides power to operate the manipulators, sensors, lights, etc, and most importantly it provides the "intelligence" necessary to make the "decisions". The tether also causes difficulty in maneuvering, limitations in range, and requires massive complex support ship handling equipment. Numerous ROVs have been lost when their tether has been snagged, or severed by the support ship. The current path for the ROV community is toward a large computer in the support ship to allow the use of high level commands and reduce the current need for highly skilled operators. Regardless, the tether's presence, particullary in deep water will continue to increase the size of the ROV, require larger thrusters, and generally make the operation more complex.

Removal of the tether allows the ROV to work inside structures, sunken ships, or under-ice without the risk of entanglement. Untethered ROV's are already in the experimental stage. Numerous technical challenges exist;

- Power is no longer supplied from the surface and the ROV must store or generate its own power. This greatly reduces the capacity for heavy work.
- The "intelligence" has been removed, the mission must be preprogramed or remote control signals transmitted through the ocean.

2. Autonomous Underwater Vehicle Development

Several industrial, academic, and military laboratories are already working on Autonomous Underwater Vehicles (AUV):

- The French Epailard built by Societe ECA can dive to the ocean floor, take still pictures and return .
- Naval Ocean Systems Center (NOSC) is developing the Free Swimming Vehicle, which is designed to follow a set of preprogramed tracks.
- International Submarine Engineering (ISE) has developed the Autonomous Remote Controlled Submersible (ARCS). Designed as an under-ice survey vehicle, it can dive to 1200 feet, travel 23 hours at five knots and return to its launch site.
- Experimental Autonomous Vehicle East (EAVE-EAST) developed at the University of New Hampshire is designed to inspect pipe lines and off shore structures. EAVE-EAST is the most advanced AUV described publicly. It is controlled entirely by onboard microprocessors.

AUV's are still quite limited and many problems remain to be solved. To be reliable the craft must be capable of handling a wide range of operational conditions, tactical alternatives, and system failures. None of the AUVs currently under development have the ability to hover other than to turn into the current and maintain position by matching the current with the propulsion thrusters. The heading is also fixed and determined by the direction of the local current. For an AUV, this limits the possible mission scenarios. Unless the AUV can hover independent of the direction of the current, it cannot conduct close-in inspections of fixed objects or perform work tasks on underwater systems in the presence of a current.

B. THESIS GOALS

The goal of this thesis was to develop a conceptual hovering/station keeping system, as part of the Naval Postgraduate School AUV Development Program. Station keeping/hovering is defined as the ability to maintain a fixed position with respect to a stationary reference point. Not only is the location fixed but also the

heading of the vehicle, that is the heading of the AUV remains constant as the current changes its aspect relative to the bow of the AUV. The aspect of the current relative to the bow is the side slip angle (β), see Figure 1.1 . The need to consider a fixed heading is dictated by workload consideration where manipulators, or some other workpackage is being used.

CQO = Ships Heading (True)
β = Side Slip Angle (Relative)
U = Incident Current

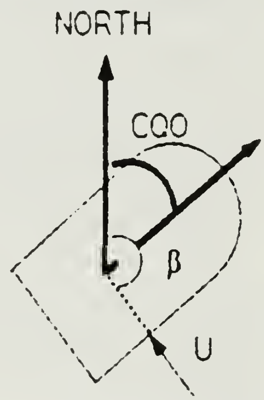

Figure 1.1 CQO and Side Slip Angle (β).

The general shape of the AUV considered in Figure 1.2, is basically a box shape with a hydrodynamic bow and a tapering stern section. In order to determine the limitation of this vehicle's ability to conduct station keeping hovering operations the hydrodynamic forces acting on the vehicle must be determined. While the final geometry of the AUV is not fixed, the following dimensions were used as baseline data for example; length = 5.5 meters, width = 2 meters, height = 1 meter (see Figure 1.2).

This thesis presents a study of thruster configurations with three and four thrusters. The best position of the lateral thrusters relative to the center of action of the AUV has been examined. To do this the hydrodynamic forces acting on the AUV were estimated for a hovering condition. Additionally different methods of distributing the forces between the different thrusters were evaluated.

Any AUV hovering/station keeping system must be capable of automatically changing from a transit mode to a hovering mode. None of the literature studied addressed how an autonomous vehicle will make the transition. While the AUV is transiting the hydrodynamic forces acting on the AUV are controlled by a combination

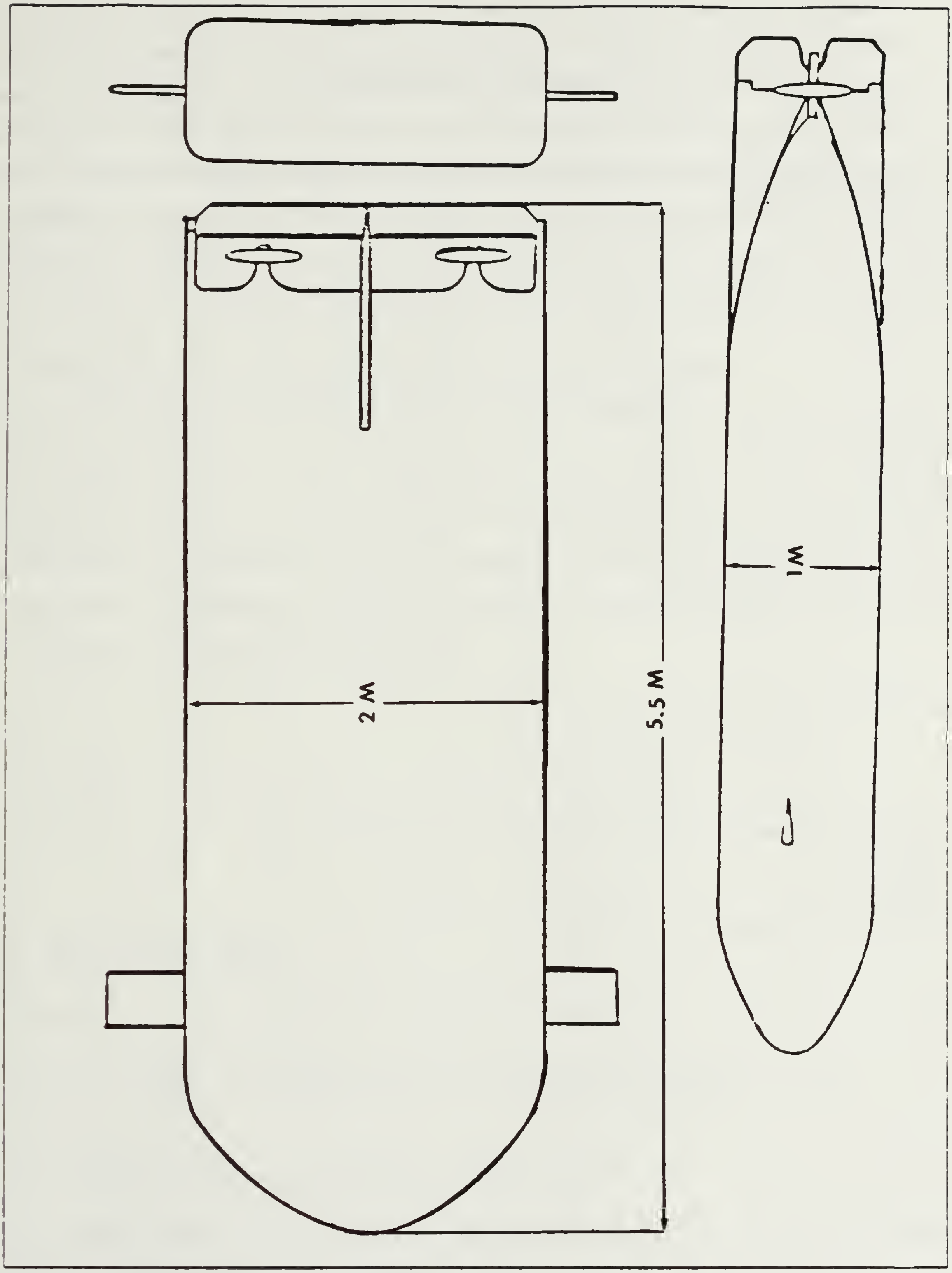

Figure 1.2 AUV Dimensions.

of thrusters and control surfaces. Whereas a hovering AUV has only the thrusters to control the forces. This thesis describes a conceptual force based control system and proposes a methodology of developing control signals based on required forces instead of the position, angles and speed commands normally used. This system will allow the smooth transition from hovering to transit modes and, will improve slow speed control of the AUV by integrating both thrusters and control surfaces to operate as needed.

II. FORCES ON THE AUV

The basic station keeping problem requires balance of the hydrodynamic forces induced on the AUV, with forces from thrusters and control surfaces. This thesis presents a study of the evaluation of the hydrodynamic forces induced on the vehicle, an analysis of various combinations of thrusters, their location, and the associated power requirements. From this analysis, the feasability of station keeping was evaluated over a given range of current, speed, and side slip angles.

For the purposes of this thesis the AUV was considered to be neutrally buoyant, with the center of gravity (CG) below the center of buoyancy (CB), and the value of GB small. The actual locations CB and CG would be determined in the final AUV design. The AUV was also considered to be hydrostatically stable in heel and trim. With the AUV submerged the affects of wind and interaction of the free surface on the hull were not considered. Although important in general, the effects of waves were considered beyond the scope of this work.

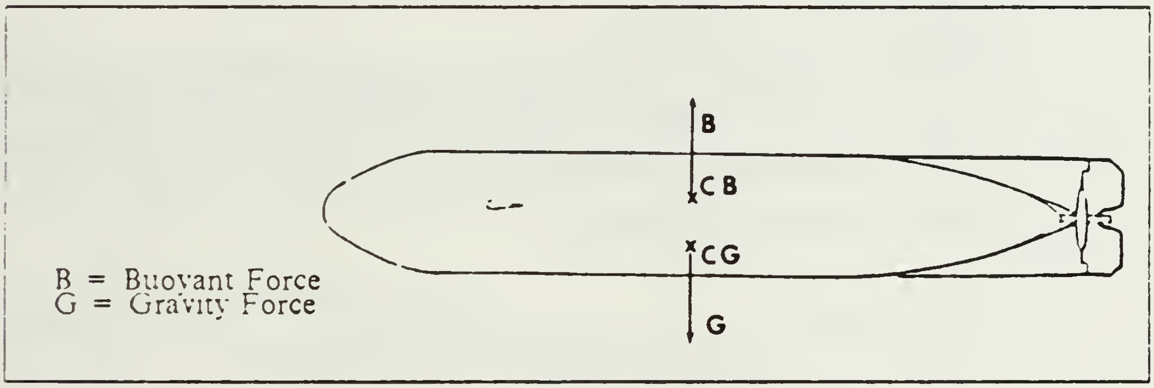

Figure 2.1 Location of Center of Bouyance and Center of Gravity.

A. HYDRODYNAMIC FORCES ON THE AUV

Sarpkaya and Isaacson [Ref. 2: p. 31], gave the general forces acting on a body at rest in a unidirectional time dependent flow as;

$$F = 0.5\, Cd\, \rho\, Ap\, |U|\, U + \rho\, (1 + Ca)\, \nabla\, du/dt \qquad \text{(eqn 2.1)}$$

Cd = Drag Coefficient

ρ = Density of Fluid

Ca = Added Mass Coefficient

U = Velocity of Flow(M/S)

∇ = Volume of the Body

Ap = Projected Area

When the body was subjected to a displacement X, velocity X′, and acceleration X″ in the direction of the incident current the equation became;

$$F = 0.5 C_d \rho A_p |U - x'|(U - x') + \rho \nabla (1 + C_a) dU/dt + (U - x') dU/dx - \rho \nabla C_a x'' \qquad \text{(eqn 2.2)}$$

The first term of equation 2.2 represented the form drag; the second term represented the local and convective accelerations of the fluid about the body; the third term was the inertial force due to the motion of the body. The sign of the last term is due to added mass of the body opposing the acceleration of the body. It acts in the opposite direction of the drag and inertial forces acting on the body.

B. STEADY FLOW ON THE AUV

This study was limited to considereation of steady flow without waves on vehicle motion. While this was clearly not representive of experience in an open ocean environment, it allowed the study of the feasibility of station keeping. With these restrictions the Force equation reduced to;

$$F = 0.5\ Cd\ \rho\ Ap\ U^2 \qquad \text{(eqn 2.3)}$$

The geometry of the AUV considered was neither axisymetric nor a body of revolution. Theoretical methods of drag determination described by White of the, David W.Taylor Naval Ship Research and Development Center, was not directly applicable [Ref. 3]. The technique to estimate the hydrodynamic forces was to take the components of U in the x and y directions and compute a separate force in each direction. This was simular to the method Nomoto and Hattori used [Ref. 4: pp. 220-228].

The forces on the body were estimated using the drag in X and Y with the components of the current in each direction from equation 2.3 .

$$X = 0.5\ Cd_x\ Ap_x\ \rho\ U_x^2 \qquad \text{(eqn 2.4)}$$

$$Y = 0.5\ Cd_y\ Ap_y\ \rho\ U_y^2 \qquad \text{(eqn 2.5)}$$

C. ESTIMATION OF THE MOMENT ABOUT Z

The AUV geometry resulted in the center of gravity being displaced from the center of action of the hydrodynamic forces. The center of action was assumed to be on the center line and at the L/2 position. This difference caused a moment about the Z axis (yaw) when ever the current was displaced from the bow. The moment was described by;

$$M_B = (X^2 + Y^2)^{1/2}\ \Delta \cos(90 - \beta) \qquad \text{(eqn 2.6)}$$

where Δ was the offset between the center of action and the center of gravity.

In addition to the X, Y, and Mz forces induced on the body, the rudder and its interaction with the current induced an additional moment equal to;

$$M_r = F_r\ L_r \qquad \text{(eqn 2.7)}$$

$$F_r = 0.5\ Cd_r\ Ap_r\ \rho\ U_y^2$$

L_r = Length from L/2 to Rudder Center Line

D. COEFFICIENT DETERMINATION

The bow was an elliptical shape and the sides were flat with rounded edges to reduce drag. A $Cd_x = 0.35$ and $Cd_y = 0.6$ were used to estimate the forces induced. The basis for choosing these values was somewhat arbitrary, but Table 7.2 in White [Ref. 6] and Figure 23 in Horner [Ref. 5: p. 3-13], indicated that these would be reasonable values to be expected from a vehicle of this general shape and size. At the conceptual design level, these values would permit reasonable power consumption

estimates. At a detailed design level, model test would be required to refine such estimates.

E. FORCES THAT MUST BE EVALUATED FOR A FINAL DESIGN

Once the final design for the vehicle is chosen a model or series of models can be developed and used to determine an equation of $Cd(U,\beta)$ that can be used for a more precise determination of the forces. Figure 2.2 shows the change in apparent area as the angle β changes. Once the design has been finalized and the model testing completed the forces acting on the AUV can be described by;

$$F = 0.5\ \rho\ Cd(U,\beta)\ Ap(\beta)\ U^2 \qquad \text{(eqn 2.8)}$$

for static forces.

The current can be measured by a weather vane type device which would give both a direction and velocity for the incident current as described in [Ref. 7: p. 3-79]. The signal from this device can be integrated with the outputs from the Navigation and other sensors to provide the speed and direction of the incident current. The output can be used directly to estimate the forces induced on the AUV. The estimated forces are shown in Figure 2.3 .

The method utilized here allowed qualitative judgments to be made as to the magnitude of the forces required, and demonstrated whether or not this type of hovering was feasible.

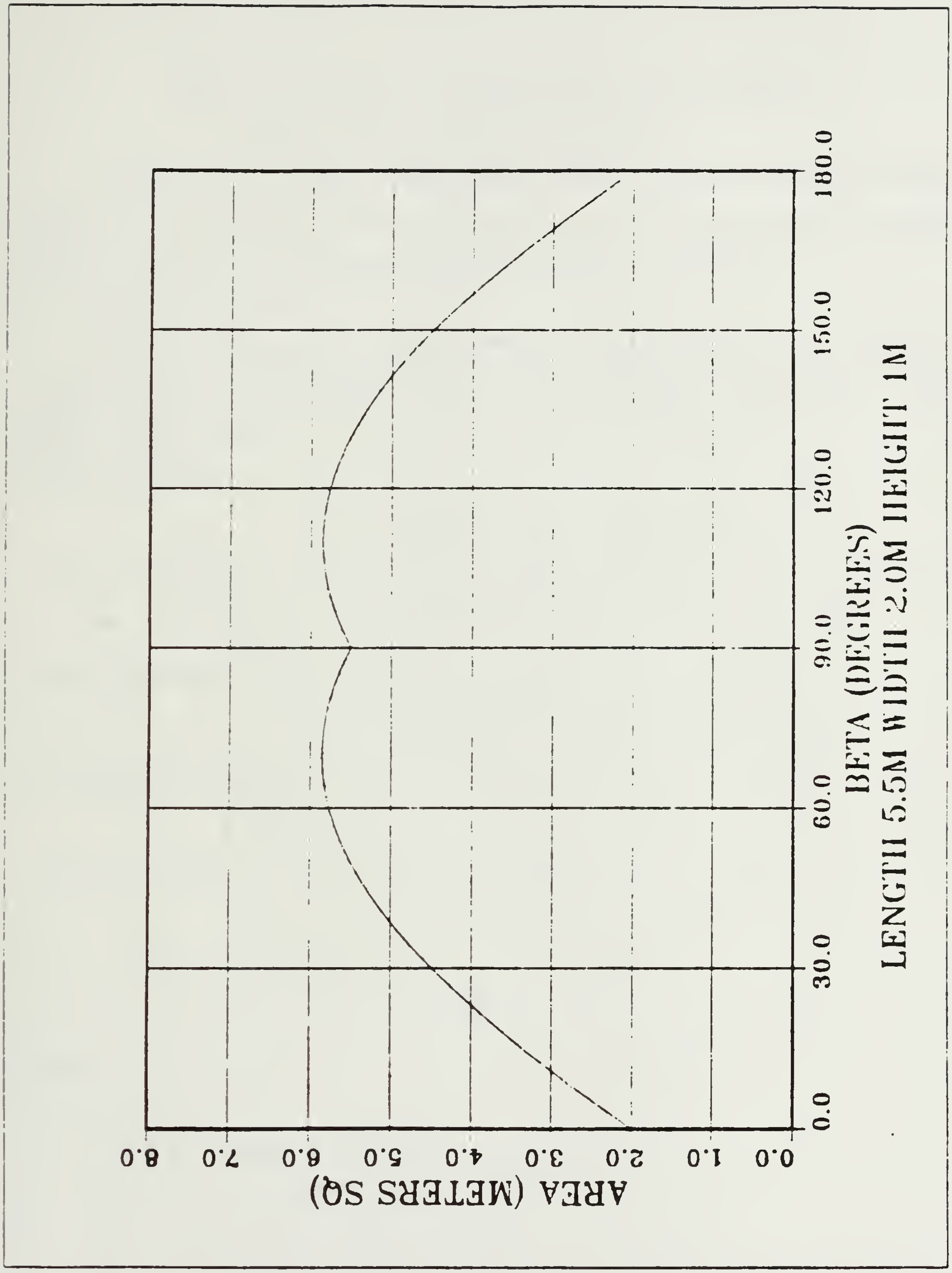

Figure 2.2 Projected Area As A Function β.

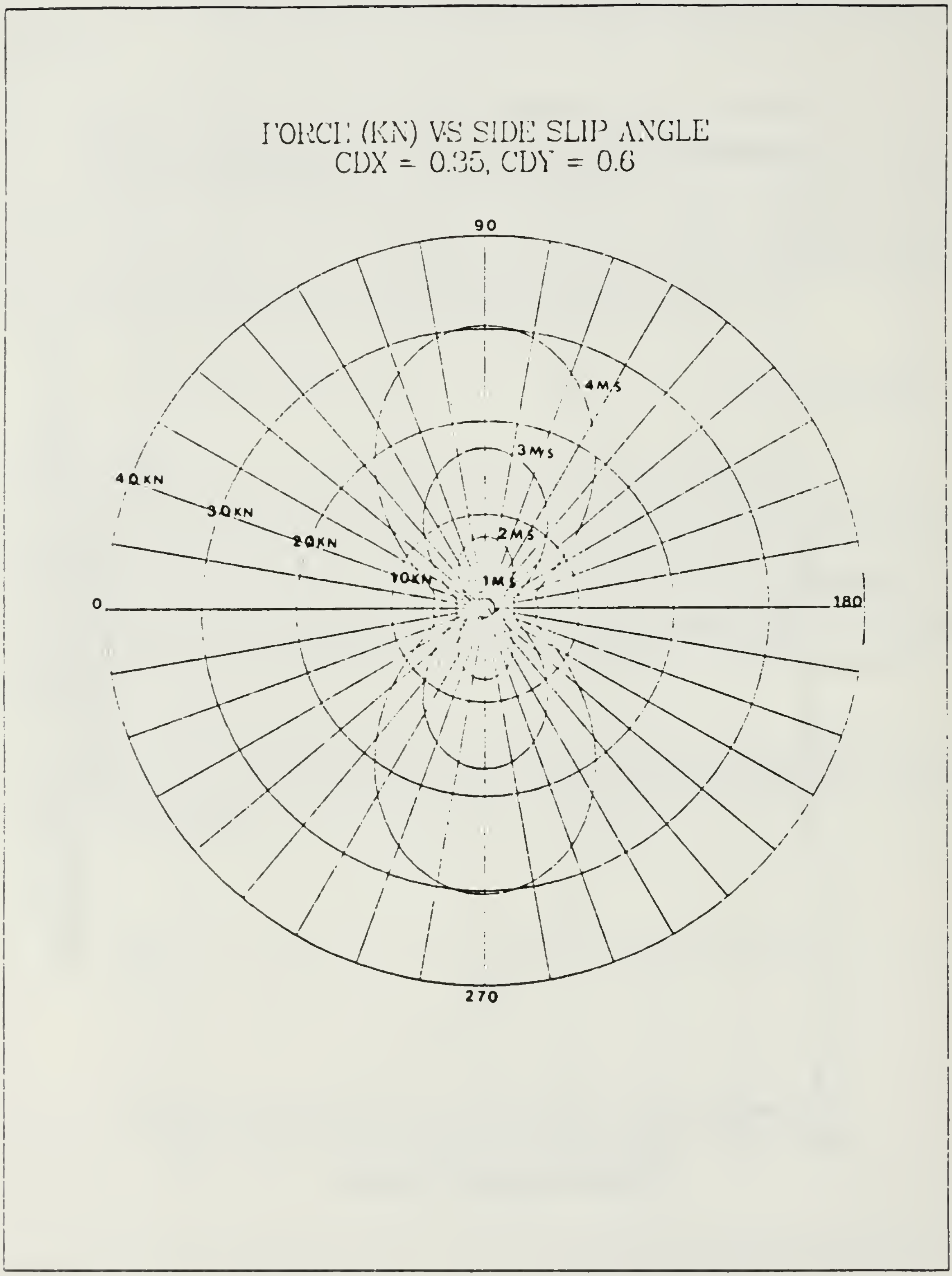

Figure 2.3 Estimated Hydrodynamic Forces Induced on The AUV.

III. COUNTERING HYDRODYNAMIC FORCES

Holding position requires that hydrodynamically induced forces be countered by mechanically induced forces from either anchors, or in this case, thrusters. This section provides a discussion of the evaluation of thrusters for this application.

A. THRUSTERS

Comstock described the theories of how propeller action provides thrust, and described the common dimensionless parameters used for propeller design [Ref. 8: Chapter VII].

Thrust Coefficient

$$K_T = \frac{T}{\rho n^2 D^4} \qquad \text{(eqn 3.1)}$$

Torque Coefficient

$$K_Q = \frac{Q}{\rho n^2 D^5} \qquad \text{(eqn 3.2)}$$

Advance Coefficient

$$J = \frac{V_A}{n D} \qquad \text{(eqn 3.3)}$$

where;

T	=	Thrust in Newtons
ρ	=	Mass Density of Water KG/M^3
D	=	Propeller Diameter in Meters
Q	=	Torque in Newton Meters
V_A	=	Speed of Advance in M/SEC
n	=	Revolutions Per Seconds

While hovering the AUV has zero speed of advance - a 'bollard pull condition'. Y. A. Isin described a technique for estimating the bollard pull for a specific propeller [Ref. 9]. This method was useful for evaluating the performance of different propellers but required specific information on propellers not yet selected. Isin's method was mentioned here for future reference and provided a useful method for the final propeller design and selection process. Beveridge, gave a technique for designing a bow thruster based on the desired turning rate [Ref. 10: p. 23]. His equations were based on zero speed of advance and corresponded to a hovering condition, where the static merit coefficient was defined as;

$$C = \frac{0.00182\, T^{3/2}}{SHP\,(\rho\, \pi\, D^2/4)^{1/2}} \qquad \text{(eqn 3.4)}$$

T	=	Total Lateral Thrust in Newtons
D	=	Duct Diameter in Meters
SHP	=	Shaft Horsepower
ρ	=	Mass Density KG/M^3

This expression was derived from momentum theory and gave ideal values of Cmax = $\sqrt{2}$ for unshrouded propellers and Cmax = 2 for ducted propellers. Solving for SHP gives;

$$SHP = \frac{0.00182\, T^{3/2}}{C\,(\rho\, \pi\, D^2/4)^{1/2}} \qquad \text{(eqn 3.5)}$$

Beveridge gave several values of C ranging from 0.55 to 1.5 for different thrusters [Ref. 10: p. 11]. The Deep Submergence Rescue Vehicle (DSRV) had values of C from 0.87 to 1.46. Of the various craft, listed the DSRV resembled the AUV the closest. Beveridge recommended a value of C = 1.0 be used for preliminary design. This was midway in the range of the DSRV values and was used for this evaluation. He also recommended an average value of K_T = 0.45. This was consistent with propeller charts in Principles of Naval Architecture [Ref. 8: Chapter VII].

Using equation 3.5 and substituting the force desired from the thruster provided an estimate of the power required from each thruster. Table I Summarizes the values used to estimate the power required from each thruster.

TABLE 1

VALUES USED TO ESTIMATE SHAFT HORSEPOWER

C	=	1.0
K_T	=	0.45
D	=	1/3 METER
T	=	THRUST REQUIRED

B. POWER LIMITS FOR HOVERING

A determination of the feasibility of hovering required that power limits be established. The AUV is assumed to have two longitudinal thrusters located equal distance from the center line and one or two lateral thrusters. A Cdx = 0.35 was used to estimate the power required for a forward speed of 12 KTS.. Comstock gave the following equation for estimated horse power; [Ref. 8: Chapter VII]

$$EHP = 1/2\ Cd\ \rho\ U^3\ Ap \qquad \text{(eqn 3.6)}$$

With a projected area (Ap) of 2 square meters the estimated horse power was 110 HP. This was divided between the two stern thrusters for a value of 55 HP per thruster. For hovering the power requirement could be significant. To limit the possible impact on the overall vehicle power requirement, the lateral thrusters were limited to about 1/3 of the longitudinal thrusters power or 15 HP and the longitudinal thrusters were limited to 1/2 their maximum or 25 HP. These limits were chosen to ensure the hovering power requirement was less than the full speed propulsion power requirement.

C. CAVITATION

In addition to being able to counter the forces induced on the AUV a secondary consideration for shallow water missions, was cavitation. Beveridge and Comstock gave a cavitation index; [Ref. 10,8]

$$\sigma = \frac{P_o - P_v}{1/2\ \rho\ D^2\ U^2} \qquad \text{(eqn 3.7)}$$

P_v	=	Vapor Pressure
P_o	=	$\rho\ g\ H$ = Pressure at Center Line of the Thruster
H	=	Depth in Meters

g = Acceleration of Gravity

σ should be greater than 3.5 to avoid cavitation. Solving the Kt equation for n (speed) and using a value of 3.5 for σ gave the minimum depth for operation without cavitation. For a 1/3 meter propeller at 15 shp and 25 shp the propeller speed was calculated to to be 2.21 rev/sec and 2.67 rev/sec respectively. The minimum depth to operate without cavitation was 0.096 meters for 15 shp and 0.14 meters for 25 shp. Based on these estimations cavitation was not a problem. However during model testing and the final design this should not be assumed to be true and the cavitation limits must be carefully evaluated with the final equipment configuration.

D. CONTROL SURFACES

In the hovering mode, the primary method of countering the hydrodynamic forces would utilize the thrusters, although the AUV control surfaces could also be used to aid in countering the forces. Comstock gave the nondimensional forms most commonly used for rudder and control surface forces; [Ref. 8: Chapter VIII]

$$\text{Lift Coefficient } Cl = \frac{L}{1/2\ \rho\ Ap\ U^2} \qquad \text{(eqn 3.8)}$$

$$\text{Drag coefficient } Cd = \frac{D}{1/2\ \rho\ Ap\ U^2} \qquad \text{(eqn 3.9)}$$

For this thesis the ability of the control surfaces to counter the induced forces was not considered. The control surfaces would act to minimize the power required from the thrusters. The uncertainty of the performance of the control surfaces, in a hovering condition, was the basis for not considering them. As mentioned in Chapter II, however, the rudder and it's associated moment was considered.

IV. THREE THRUSTERS TO COUNTER X, Y, MZ

This section examines the simplest method of countering the hydrodynamically induced forces on the AUV. Three thrusters were used to counter the X, Y, and Mz forces induced on the AUV. Two longitudinal thrusters on either side of the center line and one lateral thruster, are shown in Figure 4.1. The lateral thruster was evaluated forward, aft, and coincident with, the center of action for various currents. Also the position of the lateral thruster was varied with a fixed current. The possibility of removing the rudder and using cambered longitudinal thrusters was also analyzed.

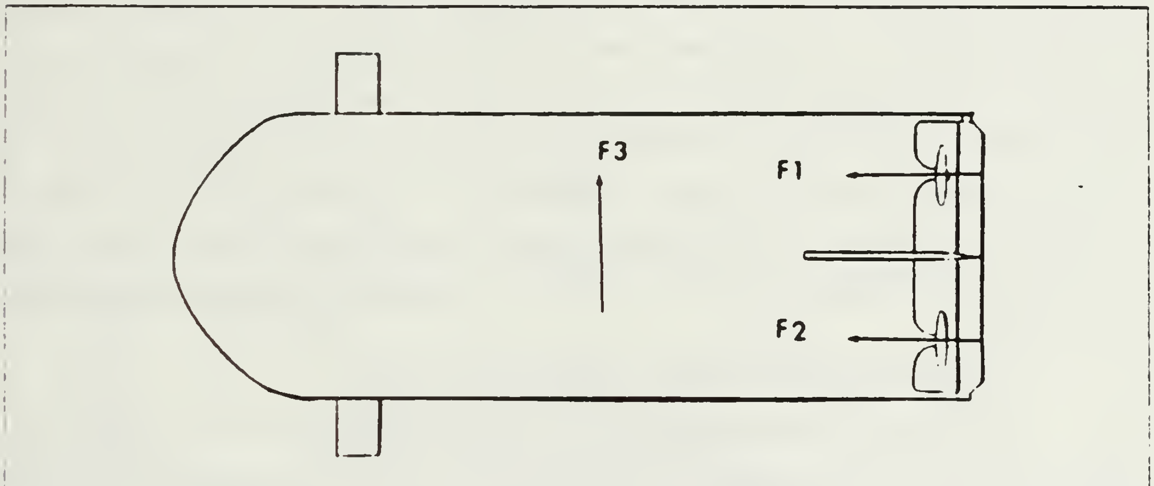

Figure 4.1 Thruster Configuration.

This configuration provided an exact solution. There were three induced forces and three unknown forces required from the thrusters. The following set of equations resulted from this configuration;

$$X = F1 + F2$$
$$Y = F3 \qquad \text{(eqn 4.1)}$$
$$Mz = L1\,F1 - L2\,F2 - L3\,F3$$

L1 and L2 were the distance from the center line to the longitudinal thruster and L3 was the distance from the center of action (L/2) for the induced forces.

These reduce to the system of equations below;

$$\begin{bmatrix} X \\ Y \\ Mz \end{bmatrix} = \begin{bmatrix} 1 & 1 & 0 \\ 0 & 0 & 1 \\ L1 & -L2 & \pm L3 \end{bmatrix} \begin{bmatrix} F1 \\ F2 \\ F3 \end{bmatrix} \qquad \text{(eqn 4.2)}$$

Which are of the form of $\underline{X} = \underline{A}\ \underline{F}$ and the solution is $\underline{F} = \underline{A}^{-1}\ \underline{X}$. The sign of the L3 coefficient was positive(+) when F3 was forward of L/2 and negative (-) when aft of L/2.

A. EVALUATION OF VARIOUS LATERAL THRUSTER LOCATIONS

These equations were evaluated for currents from 1 M/S to 3 M/S. The position of thruster F3 was varied from the L/2 position to 2 meters forward and aft. The least amount of power was required when the lateral thruster was located at the L/2 position. The limiting thruster for hovering was F3 (see Figure 4.2 and 4.3). Moving F3 forward or aft of the L/2 position did not affect the power required from F3 but it had a dramatic affect on the power required from thrusters F1 and F2. A 0.50 meter change in the position of F3 doubled the power required from F1 and F2. This was due the additional moment induced on the AUV by displacing the lateral thruster from the L/2 position.

1. Lateral Thruster Forward Of The Center Of Action

The horse power required to hover with F3 forward of L/2 (1.2 M) in currents from 1 M/S to 3 M/S exceeded the 25 HP limit. F1 and F2 exceeded the limit for all currents as seen in Figure 4.4 and 4.5 This configuration was unacceptable. With the lateral thruster F3 forward of the L/2 position, it is adding to the induced moment by an amount equal to the lateral force times the displacement of thruster F3, which must be overcome in addition to the flow induced moment on the body.

2. Lateral Thruster Aft Of The Center Of Action

Moving the lateral thruster aft of the L/2 position allowed the induced forces to be countered without aiding the Mz moment. The additional moment was in the opposite direction of Mz. Figure 4.6 and 4.7 show that this configuration also exceeded the lateral and longitudinal horsepower limits when the current exceeded 1 M/S.

3. Varying The Displacement Of F3

As the length of the lever arm is varied the power required is inversely proportional to the distance from the L/2 position. Figure 4.8 and Figure 4.9 show the

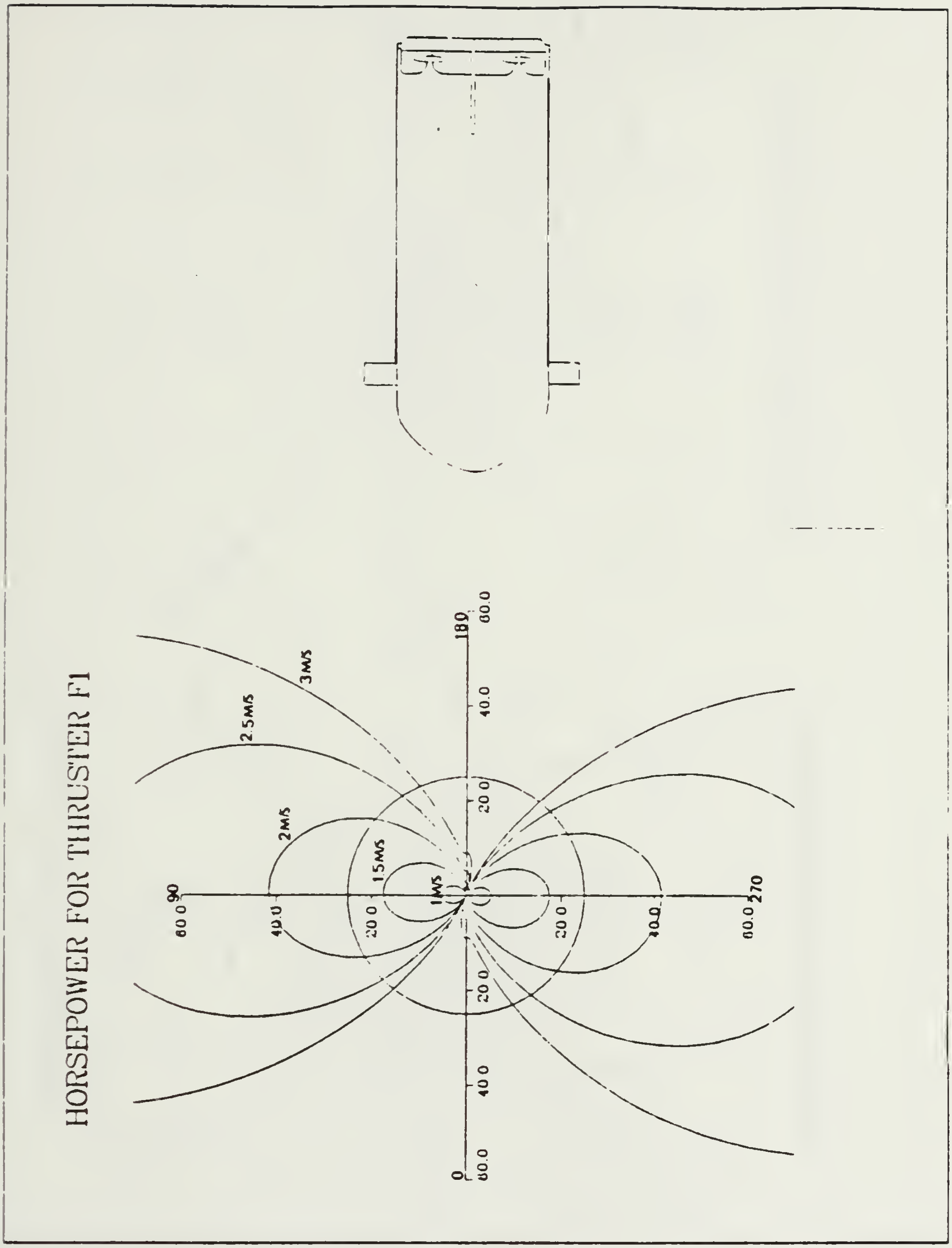

Figure 4.2 Power For F1 With The Lateral Thruster
At The Center of Action As Current Varies From 3 M/S To 1 M/S.

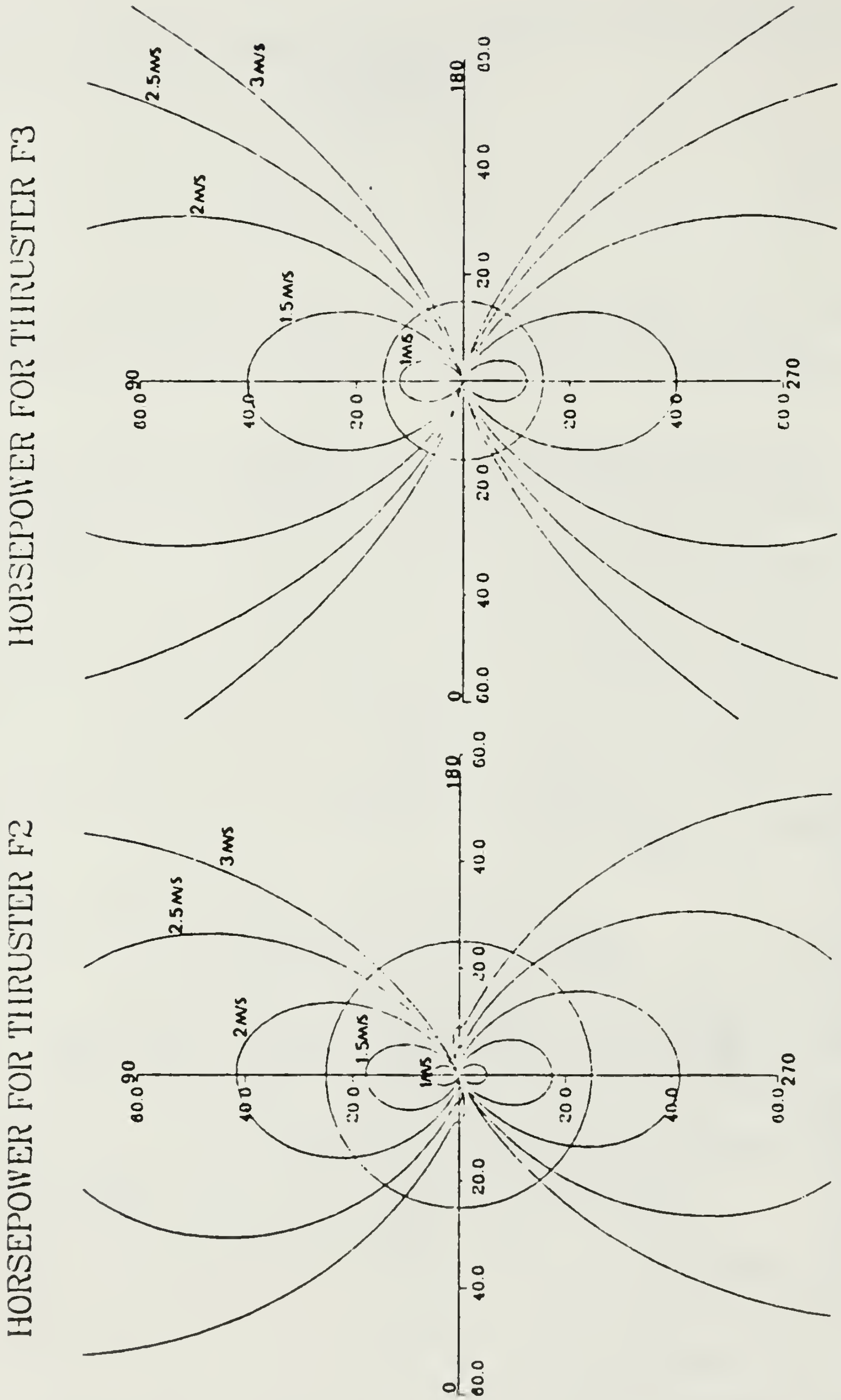

Figure 4.3 Power For F2 and F3 With The Lateral Thruster At The Center of Action As Current Varies From 3 M/S To 1 M/S.

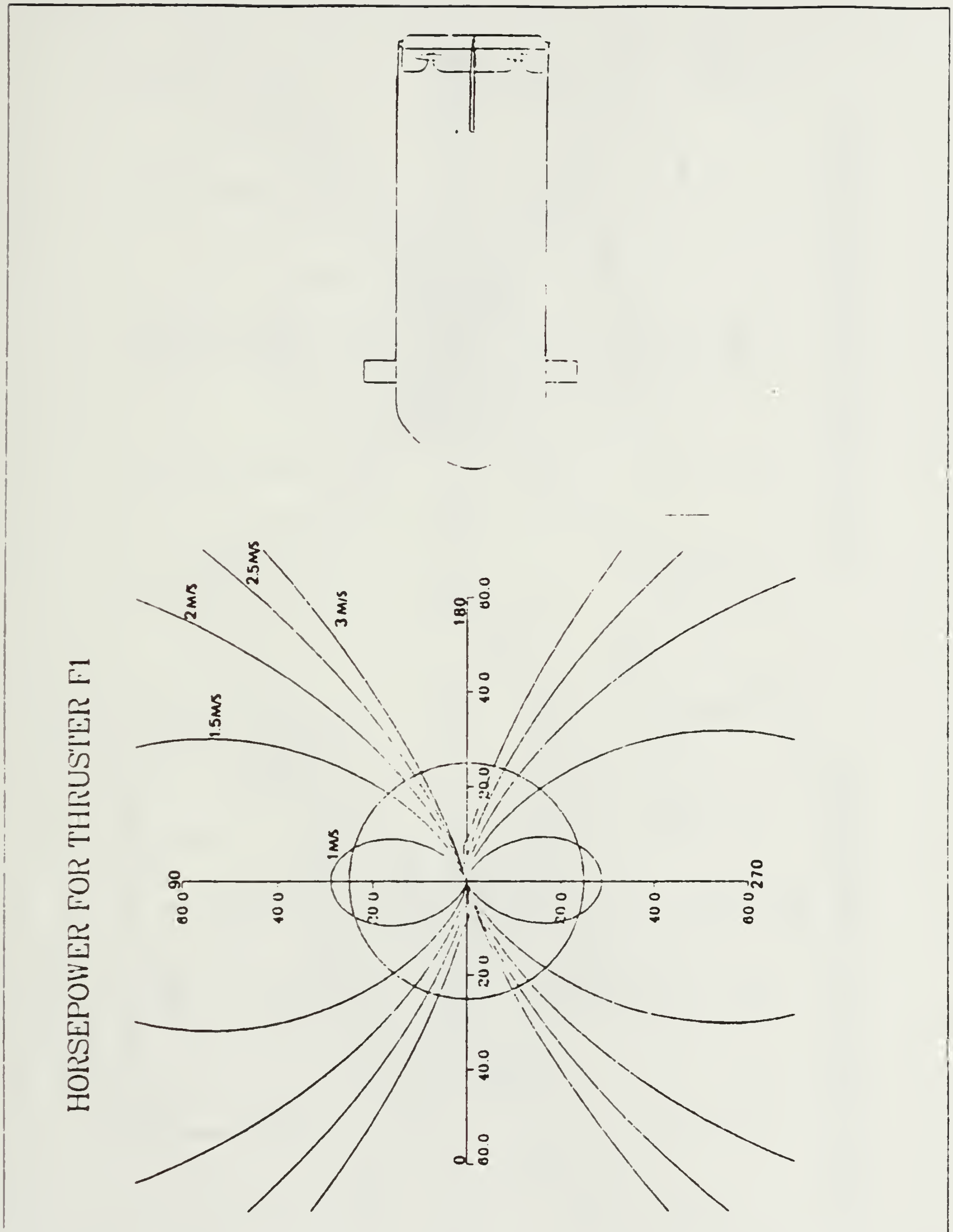

Figure 4.4 Power For F1 With The Lateral Thruster 1.2 Meters Foward of the Center of Action.

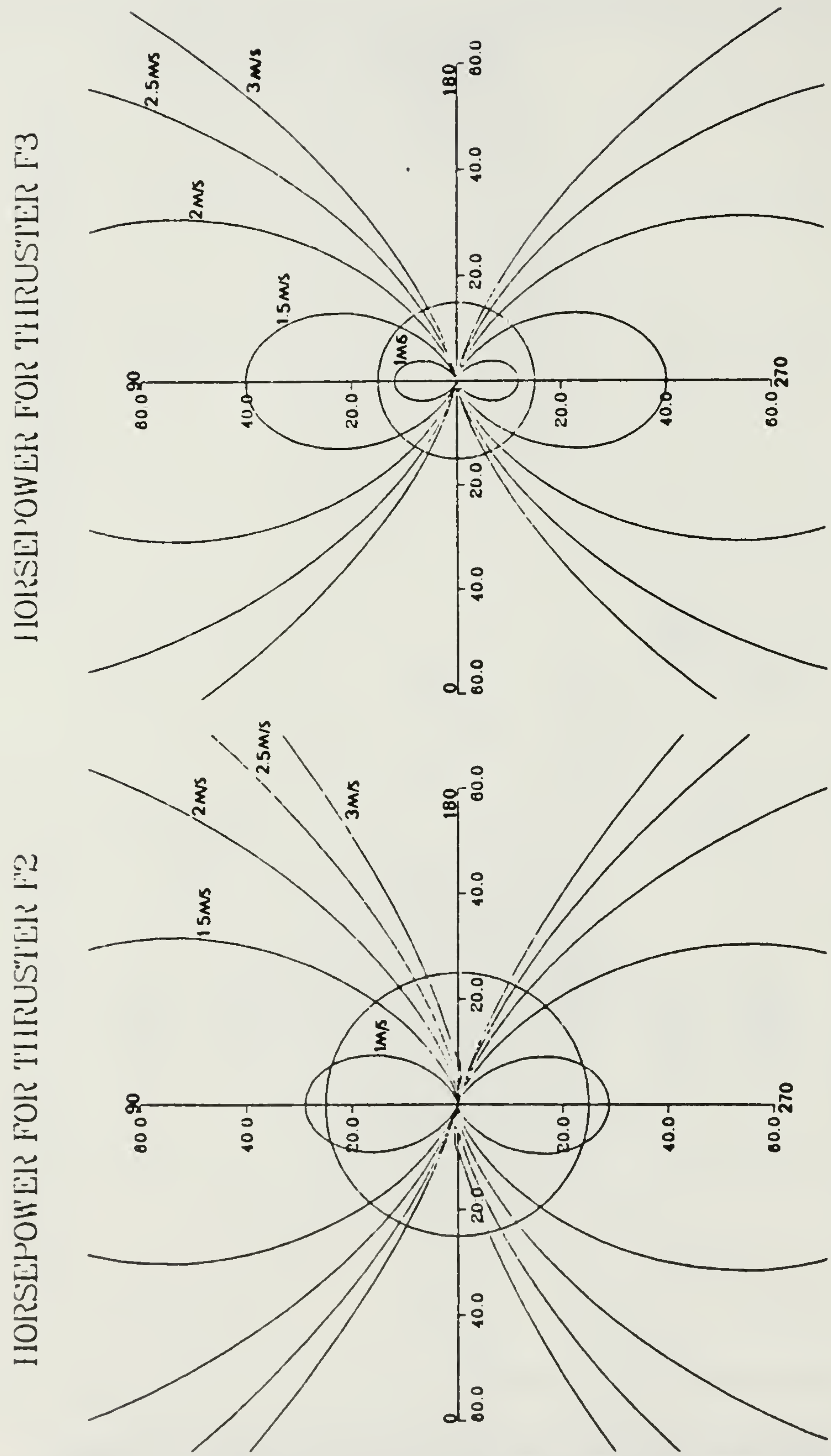

Figure 4.5 Power For F2 and F3 With The Lateral Thruster 1.2 Meters Foward of the Center of Action.

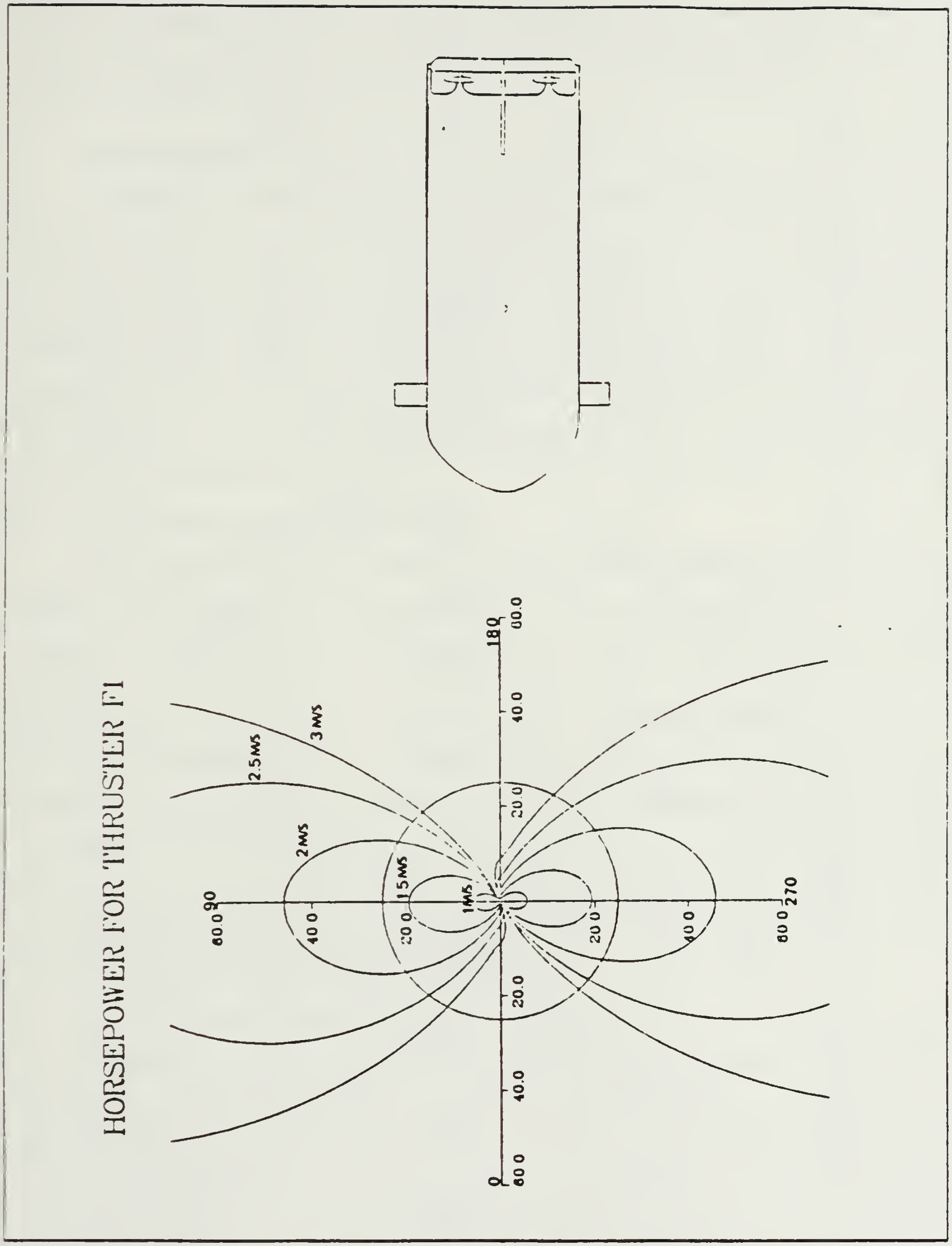

Figure 4.6 Power For F1 With The Lateral Thruster 1.2 Meters Aft of the Center of Action.

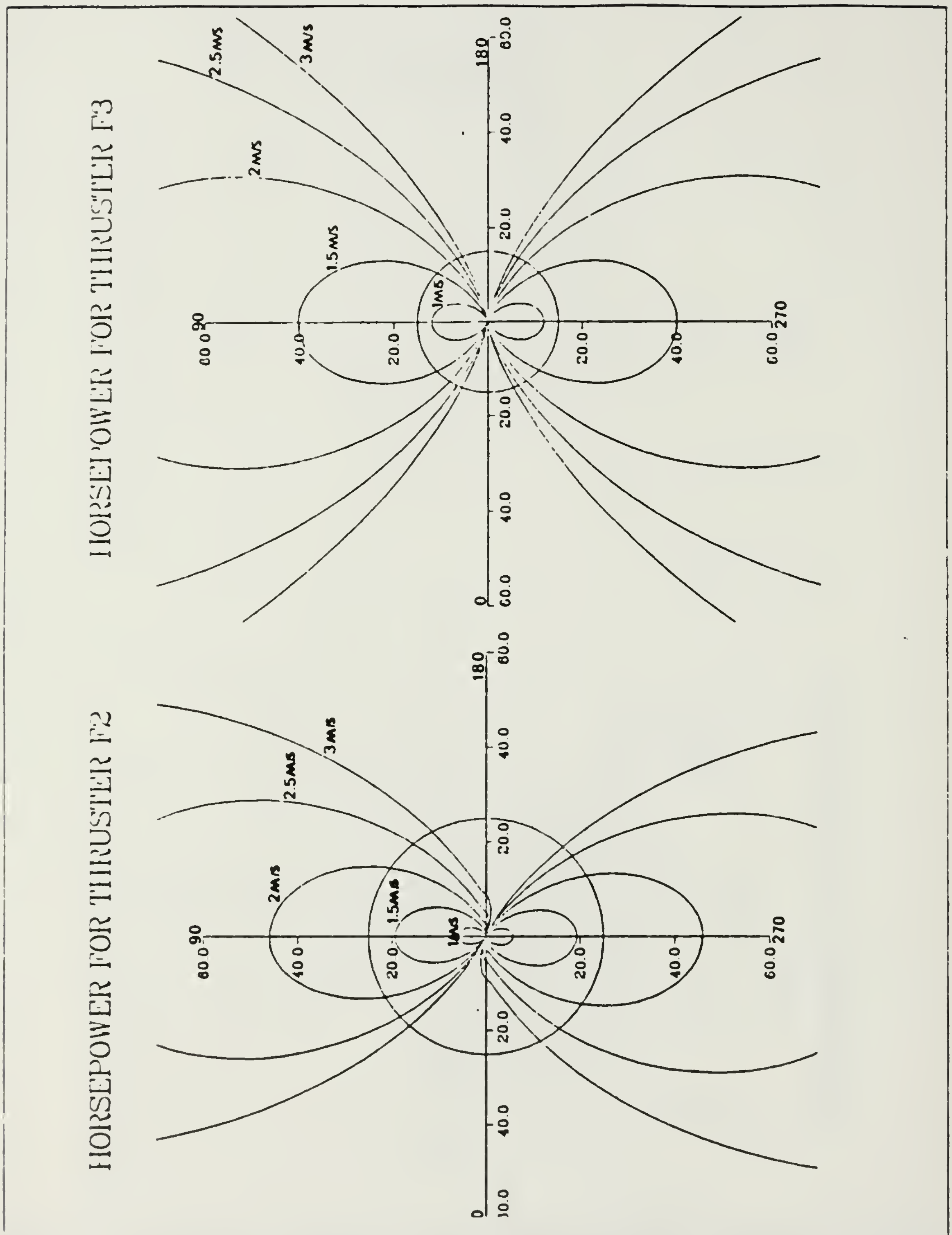

Figure 4.7 Power For F2 and F3 With The Lateral Thruster 1.2 Meters Aft of the Center of Action.

effect of varying the position of the lateral thruster. When the current was less than 1.2 M/S the power was within the limits for lever arms less than 1.3 meters. When the current was 1.5 M/S, F3 exceeded the limits.

B. RUDDER EFFECTS

Evaluation of this configuration without the rudder gave satisfactory results. The power required was below the limits for lateral and longitudinal thrusters. These results are shown in Figures 4.10 and 4.11. This indicates that the rudder model and the actual rudder are important to the ability of the AUV to hover. The rudder as modeled here was probably too restrictive i.e. the drag coefficient was high. This was intentional, if the AUV modeled can hover within the given limits, the feasibility that the subsequent AUV's will be able to hover is enhanced i.e. the conceptual study is more restrictive than the final design.

C. CAMBERED STERN THRUSTERS

Removing the rudder reduced the force required because the moment was reduced. But to control the heading without a rudder required that the thrusters be cambered. Depending on the degree of camber the overall increase in power was small, 3.5% for a 15° camber and 1.5% for a 10° camber. However, the AUV was dynamically unstable when the side slip angle was between 90° and 270° . The resultant line of action of the cambered thrusters was forward of the L/2 position, when β was greater than 90° the resultant force from the thrusters and the force from the current acting on the AUV were unstable. Any misalignment in the two forces resulted in a moment on the AUV which tended to rotate the body instead of holding it in position, this is illustrated in Figure 4.12. This inherent instability of the cambered thruster configuration makes it unacceptable.

D. THREE THRUSTER SUMMARY

When three thrusters were used, the best position for the lateral thruster was at the center of action(L/2). Whenever the lateral thruster must be moved from this position additional moments on the AUV must be over come. Given that the lateral thruster must be moved, it was best to move it aft. Moving it aft induced a moment in the opposite direction of the current induced moment Mz. Moving away from the L/2 position exceeded the power limits when the lateral thruster was moved more than 1.3 meters and the current exceeded 1 M/S.

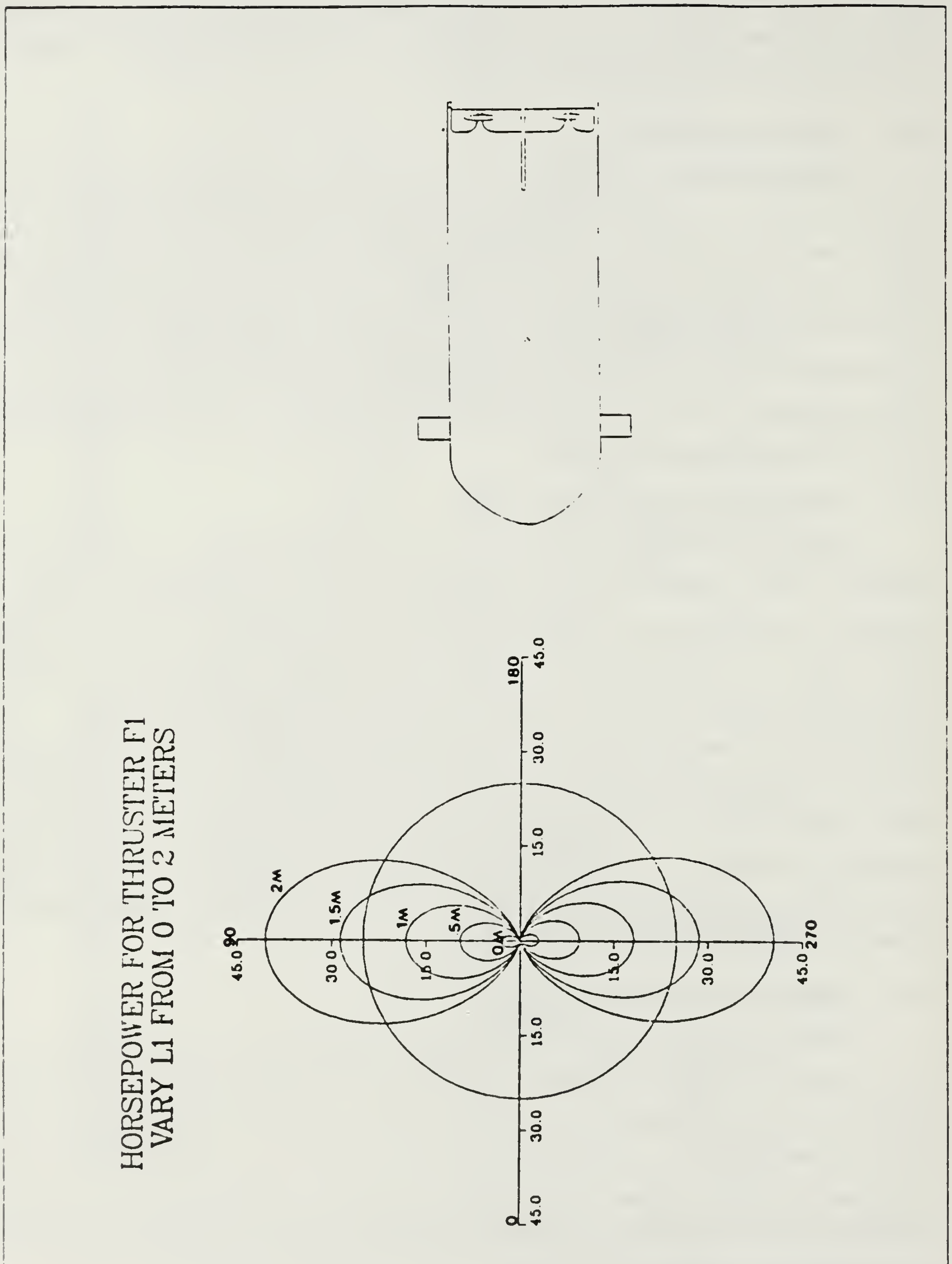

Figure 4.8 Effect Of Position of The Lateral Thruster in a 1.5 M/S Current.

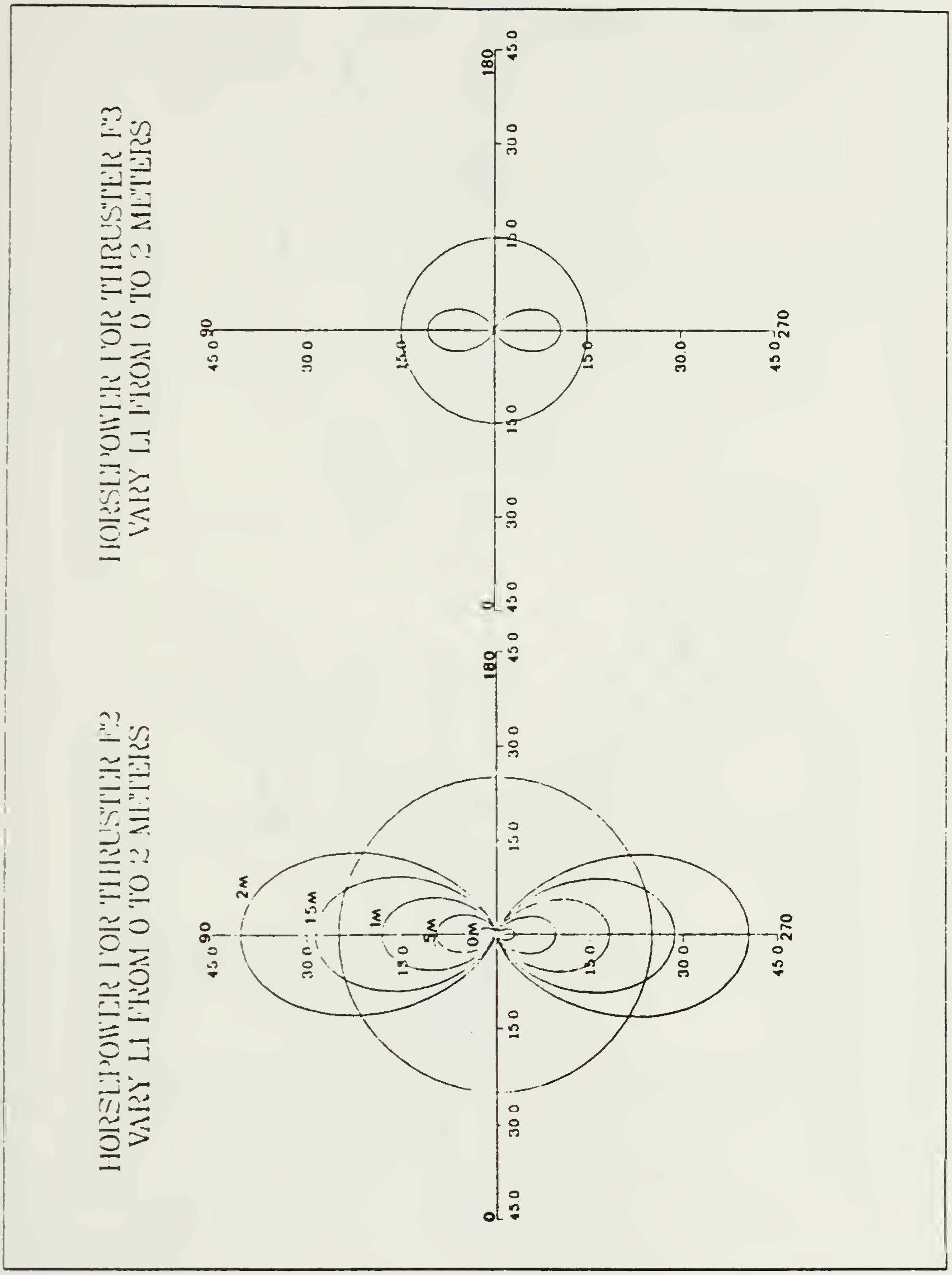

Figure 4.9 Effect Of Position of The Lateral Thruster in a 1.5 M/S Current.

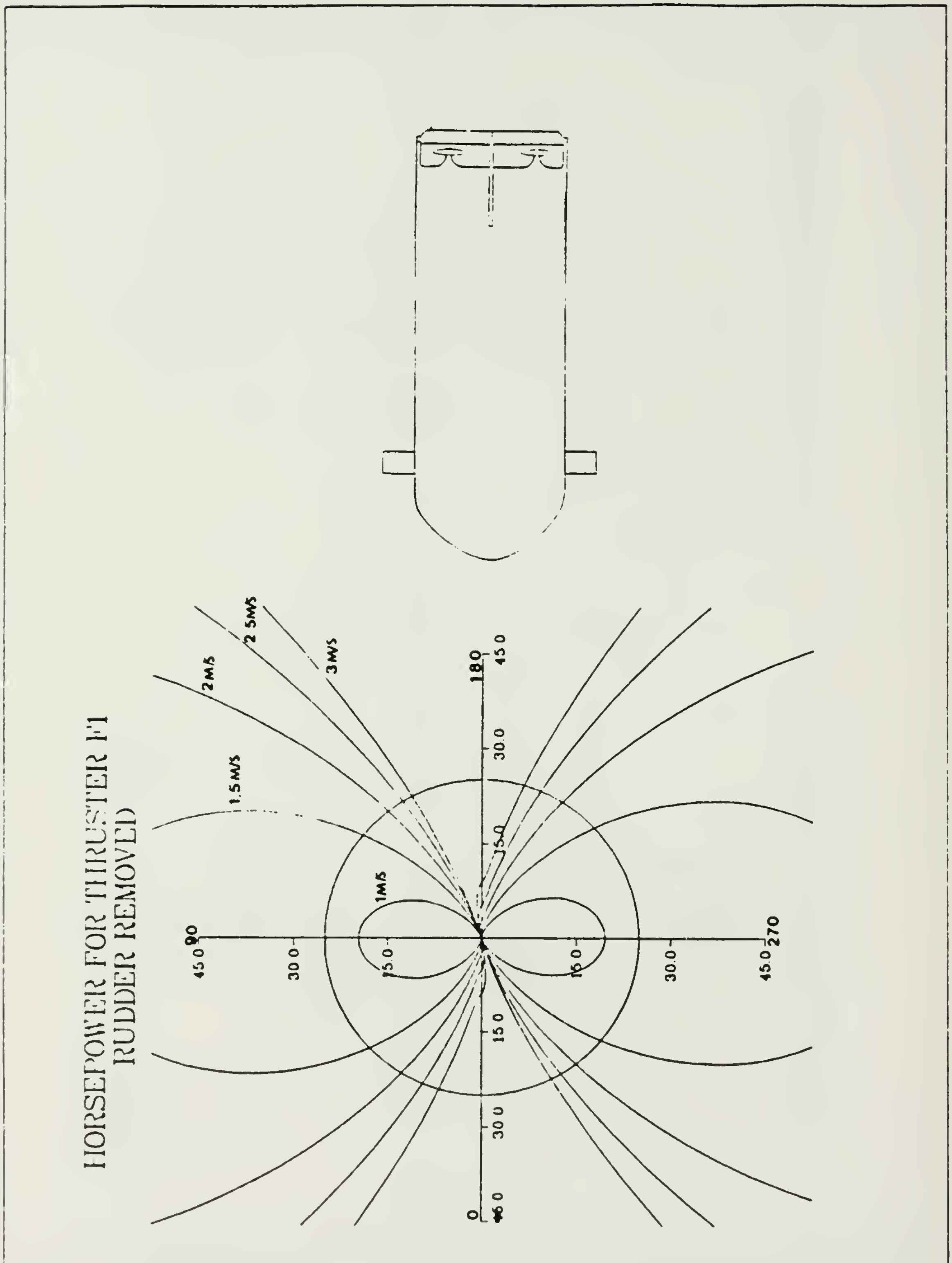

Figure 4.10 Effects Of Removing The Rudder.

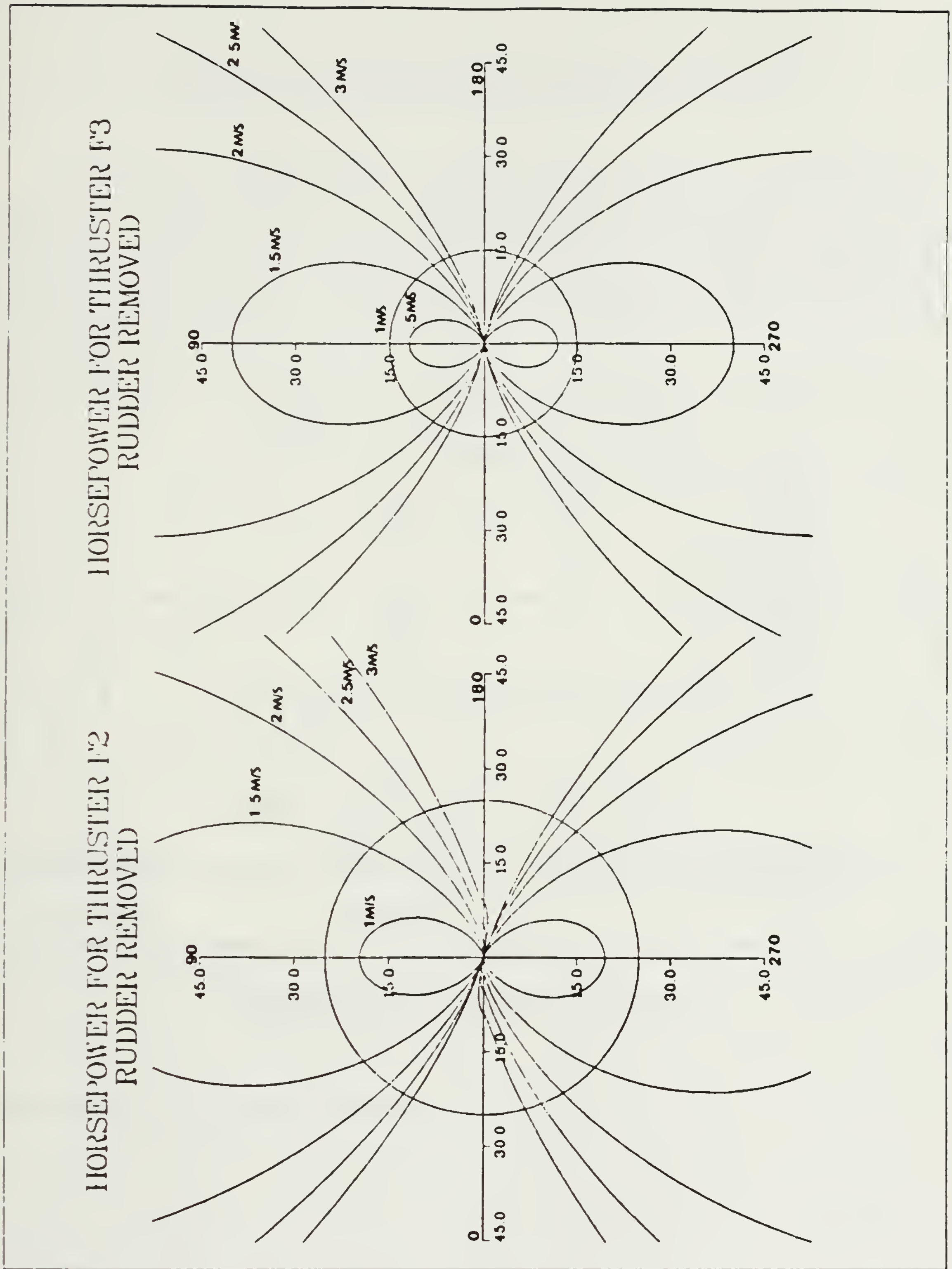

Figure 4.11 Effects Of Removing The Rudder.

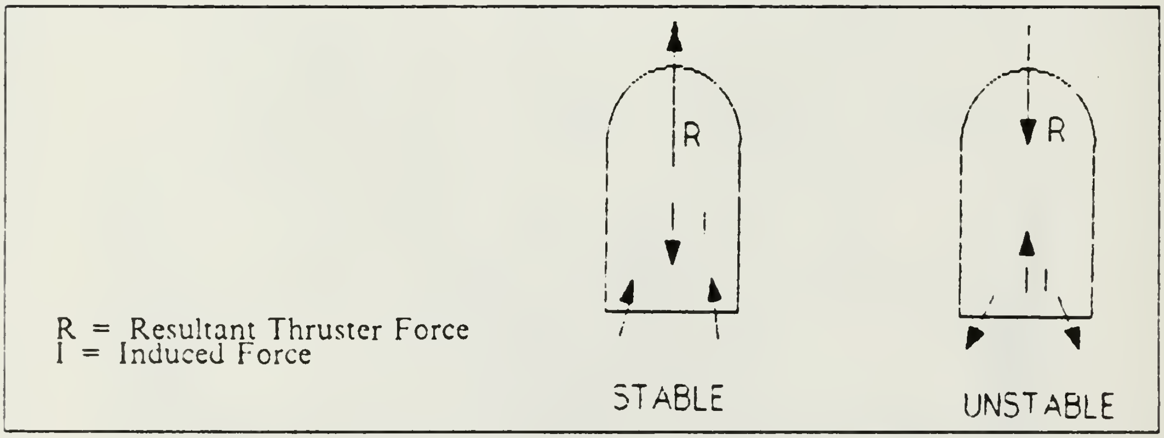

Figure 4.12 Cambered Thruster Instability.

V. FOUR THRUSTERS TO COUNTER X, Y, MZ

To achieve a more fuel efficient solution to hovering power consumption, four thrusters,(two longitudinal, and two lateral) were studied for countering the X,Y, and Mz forces. The longitudinal thrusters were in the same position as the three thruster case described in Chapter IV. The lateral thrusters were located forward and aft of the L/2 position as shown in Figure 5.1 .

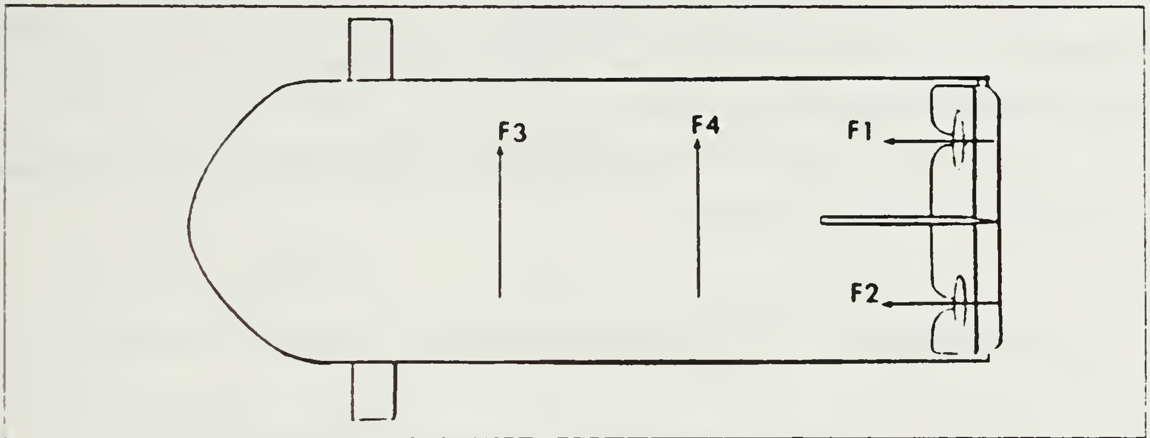

Figure 5.1 Four Thruster Configuration.

This configuration resulted in the following set of equations;

$$\begin{aligned} X &= F1 + F2 \\ Y &= F3 + F4 \\ Mz &= L1\,F1 - L2\,F2 - L3\,F3 + L4\,F4 \end{aligned} \qquad \text{(eqn 5.1)}$$

These reduce to the system of equations;

$$\begin{matrix} X \\ Y \\ Mz \end{matrix} = \begin{matrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ L1 & -L2 & -L3 & L4 \end{matrix} \quad \begin{matrix} F1 \\ F2 \\ F3 \\ F4 \end{matrix} \qquad \text{(eqn 5.2)}$$

This system of equations was more complex mathematically than the three thruster case. It did not have a unique solution. There are more unknowns than equations. However there are methods of finding a solution. Brogan describes a minimum norm solution technique which is utilized here [Ref. 11: p. 89].

A. MINIMUM NORM SOLUTION

The system of equations are of the form $\underline{Y} = \underline{A}\ \underline{X}$. $\underline{Y}$ represented the hydrodynamic forces on the AUV and had dimensions of 3 x 1. $\underline{A}$ was the geometric coefficients of the AUV and had dimensions of 3 x 4. $\underline{X}$ represented the unknown thruster forces and had dimensions of 4 x 1.

The object was to obtain a solution to the system of equations. A unique solution was not possible because there were more unknowns than equations, but the minimum norm solution was possible.

The norm of X = $|X|^2$ had the form $\sum [F1^2 + F2^2 + F3^2 + F4^2]$. To minimize the norm a function J was defined;

$J = | \underline{X}^T \underline{X} | + \lambda^T [\underline{Y} - \underline{A}\ \underline{X}]$

Where $[\underline{Y} - \underline{A}\ \underline{X}] = 0$ and $[\underline{X}^T \underline{X}] = |\underline{X}|^2$, and

λ^T was a 3x1 vector.

The following conditions were applied to J to yield the minimum of $|\underline{X}|^2$.

$\partial J / \partial \lambda = 0$ and $\partial J / \partial X = 0$

$\partial J / \partial X = 2\underline{X}^T - \lambda^T$

$\underline{A} = 0$ and $\partial J / \partial \lambda = \underline{Y} - \underline{A}\ \underline{X} = 0$

$\therefore 2\underline{X} = \underline{A}^T \lambda$ and $\underline{Y} = \underline{A}\ \underline{X}$

$\underline{X} = 1/2\, \underline{A}^T \lambda, \quad \therefore \quad \underline{Y} = 1/2\, \underline{A}\ \underline{A}^T \lambda$, so

$\lambda = 2 [\underline{A}\ \underline{A}^T]^{-1} \underline{Y}$,

and $\underline{X} = 1/2\, \underline{A}^T\, 2 [\underline{A}\ \underline{A}^T]^{-1} \underline{Y}$

everything on the right side is known and the solution is $\underline{X} = \underline{A}^T [\underline{A}\ \underline{A}^T]^{-1} \underline{Y}$.

B. THRUSTER EVALUATION

The thruster configuration was evaluated for currents from 3 M/S to 1 M/S with β varying from 0° to 360° . show the power required to satisfy the hovering system of equations. For the case where each thruster is weighted equally in the force balance,

the lateral thrusters exceed the the 15 HP limit for all currents (Figure 5.2 thru 5.3). Removal of the rudder lowered the power required but the problems of dynamic stability discussed in Chapter IV preclude a cambered thruster configuration.

C. WEIGHTED SOLUTION

The thrust required while equal weighting of each thruster provided an unacceptable solution, changing the 'weight' of each thruster can limit the lateral thrusters thrusters in their ability to counter the induced forces. To account for this a weighting matrix was introduced into the system of equations. The weighting matrix did not change the system other than to shift the relative weight of each equation such that the equations representing the longitudinal thrusters were 'worth' more. This resulted in the power required from the longitudinal increasing and the lateral power decreasing. The solution technique was identical to the minimum norm solution described earlier and resulted in a weighted minimum norm solution;

$$\underline{X} = \underline{W}\,\underline{A}^{T}\,[\underline{A}^{T}\underline{W}\,\underline{A}]^{-1}\,\underline{Y} \qquad \text{(eqn 5.3)}$$

By varying the weighting factors in the weighting matrix $\underline{W}$, shown below;

$$W = \begin{matrix} W_1 & 0 & 0 & 0 \\ 0 & W_2 & 0 & 0 \\ 0 & 0 & W_3 & 0 \\ 0 & 0 & 0 & W_4 \end{matrix}$$

W_1 to W_4 could be selected so that the power was shifted from the lateral thrusters to the longitudinal thrusters.

Thrusters F1 and F4 were analyzed for various weights. When all the weights were equal to one, F4 was about 25 HP at 1.5 M/S and F1 was less than ten HP for all currents from 3 M/S to 1.5 M/S. The limiting thruster was the lateral thruster as in the three thruster case. With the rudder on zero and all weights the same (1) gave the results shown in Figure 5.2 and 5.3 . This configuration was within the limits except for thruster F4. By varying the the weights for the different thrusters the hovering range was extended to 1.5 M/S. Figures 5.4 and 5.5 show the weights used and the effect of changing the relative weights. Both configurations were such that the relative weight of F1 was larger than F4 and resulted in an increase in the power required from F1 an a decrease in the power from F4.

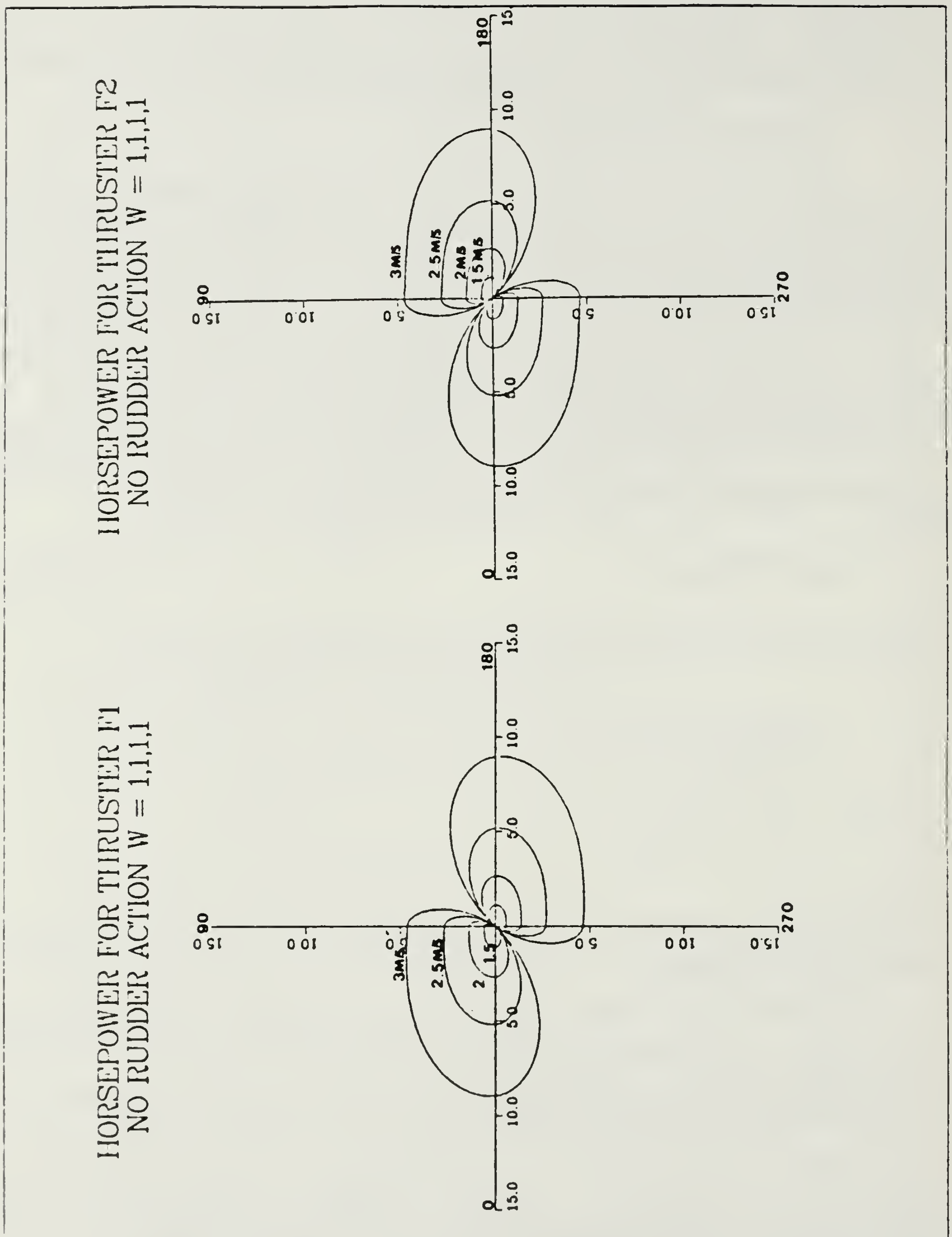

Figure 5.2 Power For F1 and F2 in Currents From 3 M/S to 1.5 M/S
Weights = 1,1,1,1.

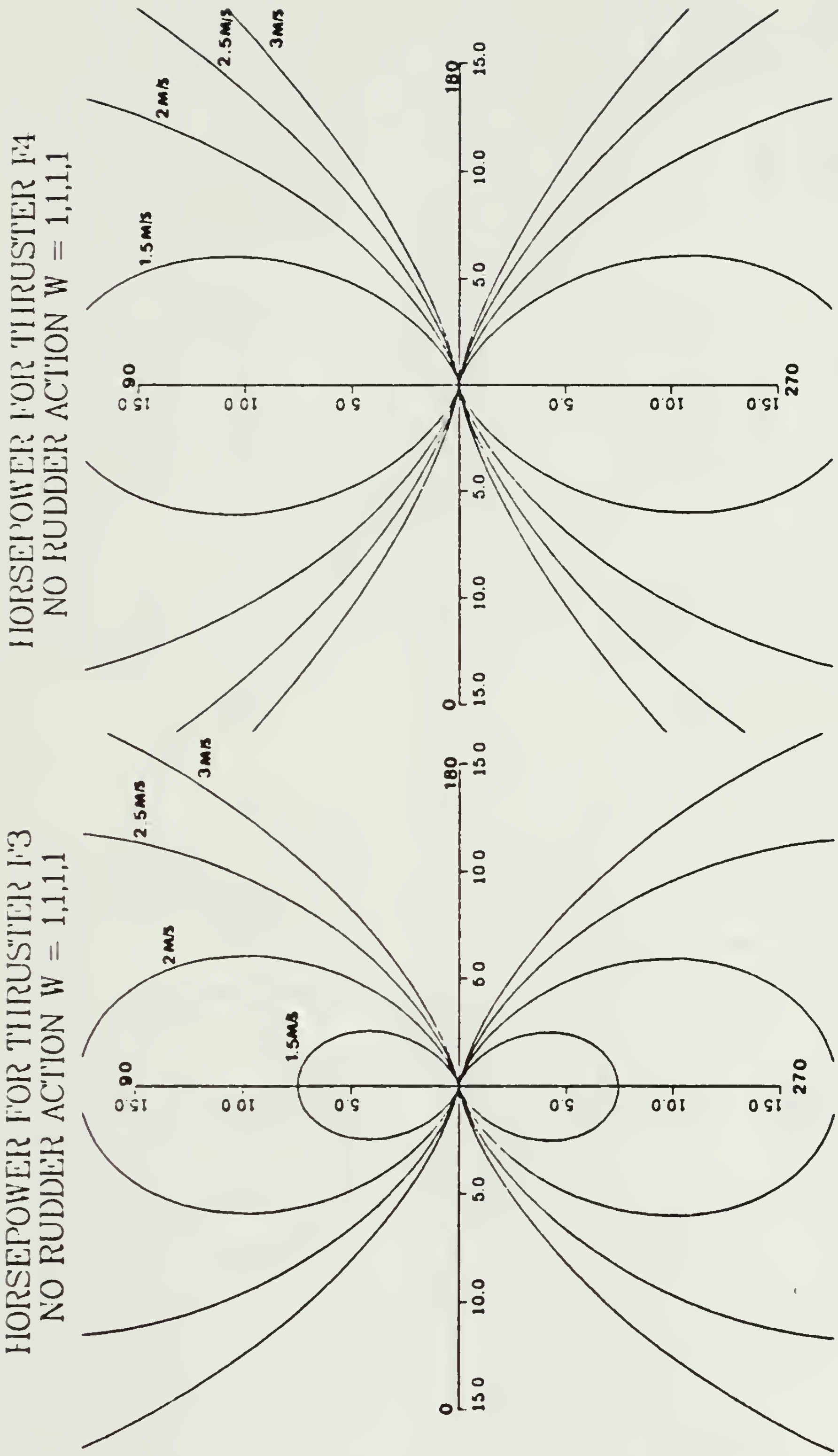

Figure 5.3 Power For F3 and F4 in Currents From 3 M/S to 1.5 M/S
Weights = 1,1,1,1.

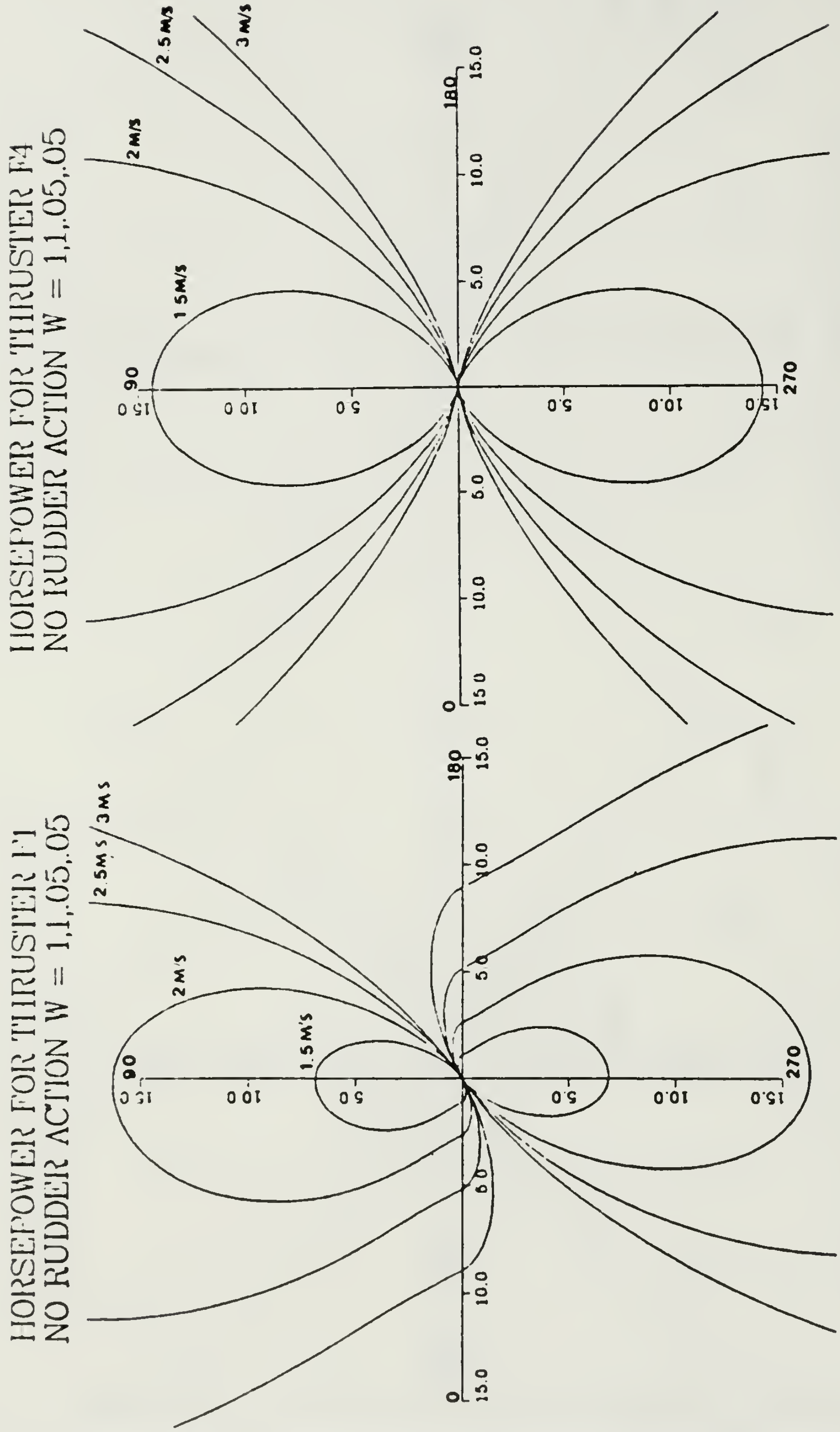

Figure 5.4 Power For F1 and F4 in Currents From 3 M/S to 1.5 M/S
Weights = 1,1,.05,.05.

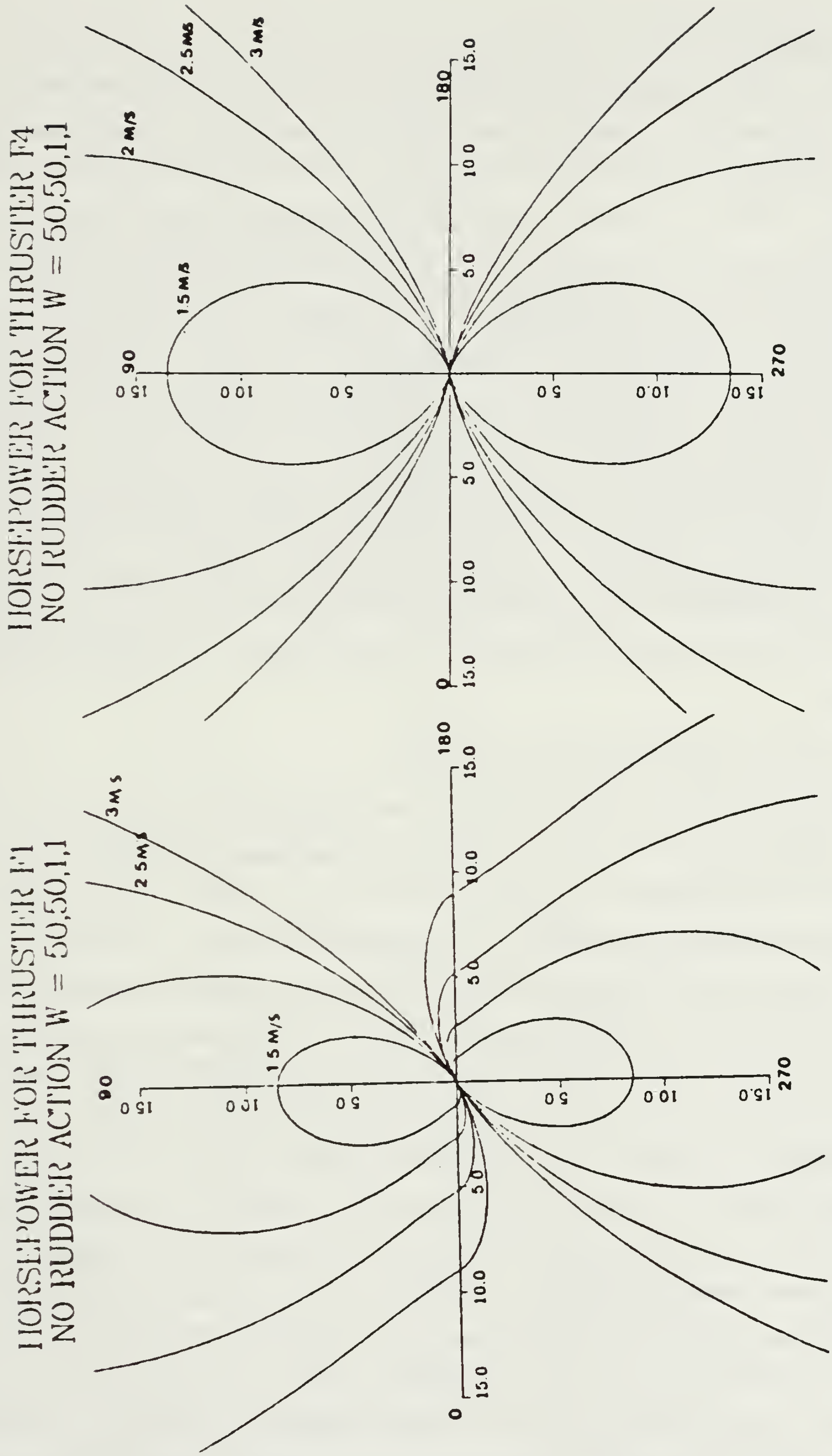

Figure 5.5 Power For F1 and F4 in Currents From 3 M/S to 1.5 M/S
Weights = 50,50,1,1.

D. RUDDER ACTION

The rudder, being fixed, for all β angles did not minimize the rudder induced moment. Moving the rudder into the current when ever possible minimized the rudder moment. The rudder was assumed to have a travel of 30 degrees on either side of the center line. When the current was in the 60 degree span (either forward or aft) the rudder was pointed into the current and this effectively eliminated the rudder moment. For currents outside this 60 degree travel the rudder was positioned such that the moment induced was minimized. This rudder action resulted in the power requirements shown in Figure 5.6 thru Figure 5.9 . When compared with the no rudder action configuration with the same weights the power was reduced in the 60 degree span around center line but it was higher outside of the region where the rudder could be pointed into the current. Additionally the moving of the rudder as the current moves around the body could result in additional moments in this thesis. These moments could cause unnecessary complications when shifting from hovering to transit modes for the AUV and should be investigated in detail before a rudder action scheme is considered.

E. LATERAL THRUSTER LOCATION

The data shown for the AUV has been developed using a 1.2 meter lateral thruster displacement from the L/2 position. To determine the lateral thruster optimum location the displacement was varied from 0 to 2 meters. Two meters was the maximum displacement because of the hydrodynamic bow. Moving the thruster further forward would disrupt the shape of the bow and result in additional drag from flow around the thruster tunnel opening in the bow. Additionally the installation in the curved portion of the bow would be more difficult than in the straight section of the hull. The thruster positions were maintained symmetric about the L/2 position. Figure 5.10 thru Figure 5.12 shows the variations in power required as the thruster position was moved from 0 to 2 meters away from the L/2 position. As the distance increased the power for F1 increased and the power for F2 decreased and similarly for F3 and F4. This made evaluation difficult. In order to better evaluate the effects of changing the displacement the sum of the thruster power(F1+F2+F3+F4) was plotted and shown in Figure 5.12. As the displacement from L/2 increased the total power decreased. This was due to the F4 thruster requiring less power to overcome the moment from the rudder with a larger lever arm. From Figure 5.12 the further the lateral thrusters were from L/2 the lower the required power.

Placing the lateral thrusters in an configuration other than symmetric about L/2 was investigated. Thruster F4 was moved to the aft most position and F3 was moved to the forward most position. The power required was significantly larger than the symmetric placements and further investigation was not considered worth while.

F. SUMMARY OF FOUR THRUSTERS

Utilizing four thrusters to counter the induced forces was more complex mathematically. This added complexity was compensated for by an increase of 0.5 M/S in the current that could be overcome. The use of the weighting matrix allowed the distribution of the forces to be shifted between the thrusters to better utilize the power available. While the rudder action minimized the induced moments the additional complications with the dynamic stability of the AUV did not make the rudder action worth while. The best configuration for four thrusters was with the largest displacement from L/2 and the relative weigths of F1 and F2 significantly larger than F3 and F4.

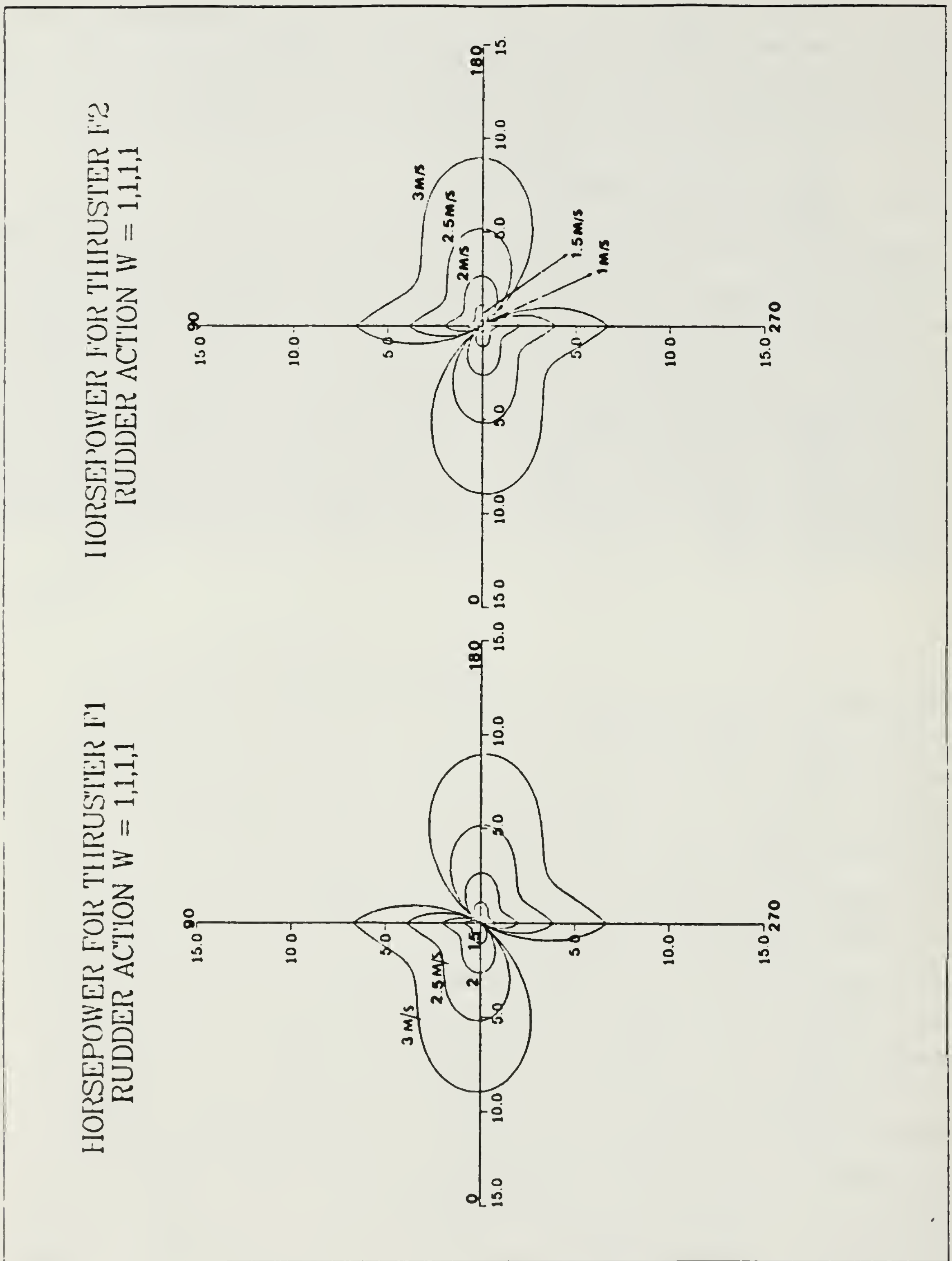

Figure 5.6 Effects of Rudder Action on F1 And F2 Power.

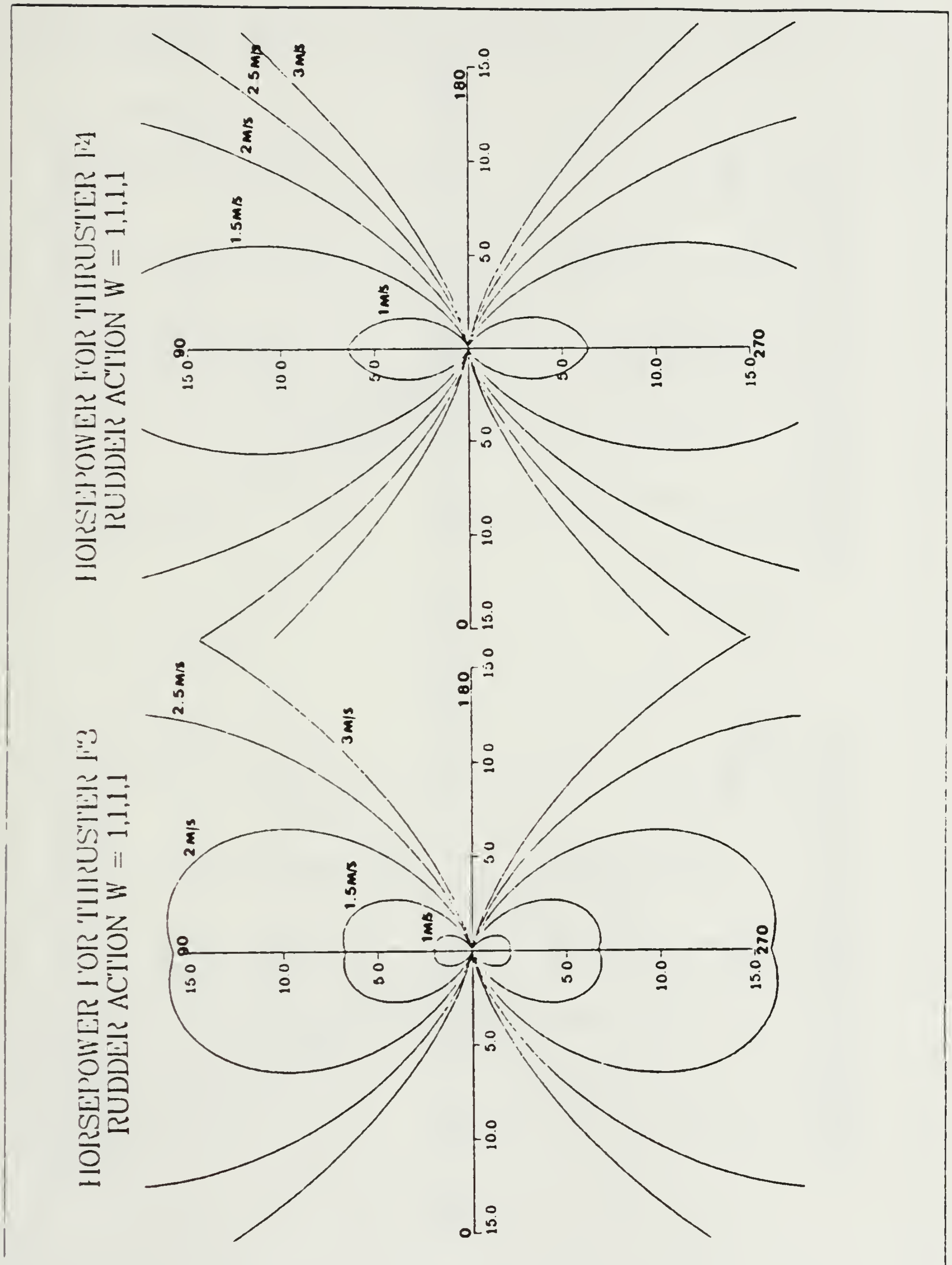

Figure 5.7 Effects of Rudder Action on F3 And F4 Power.

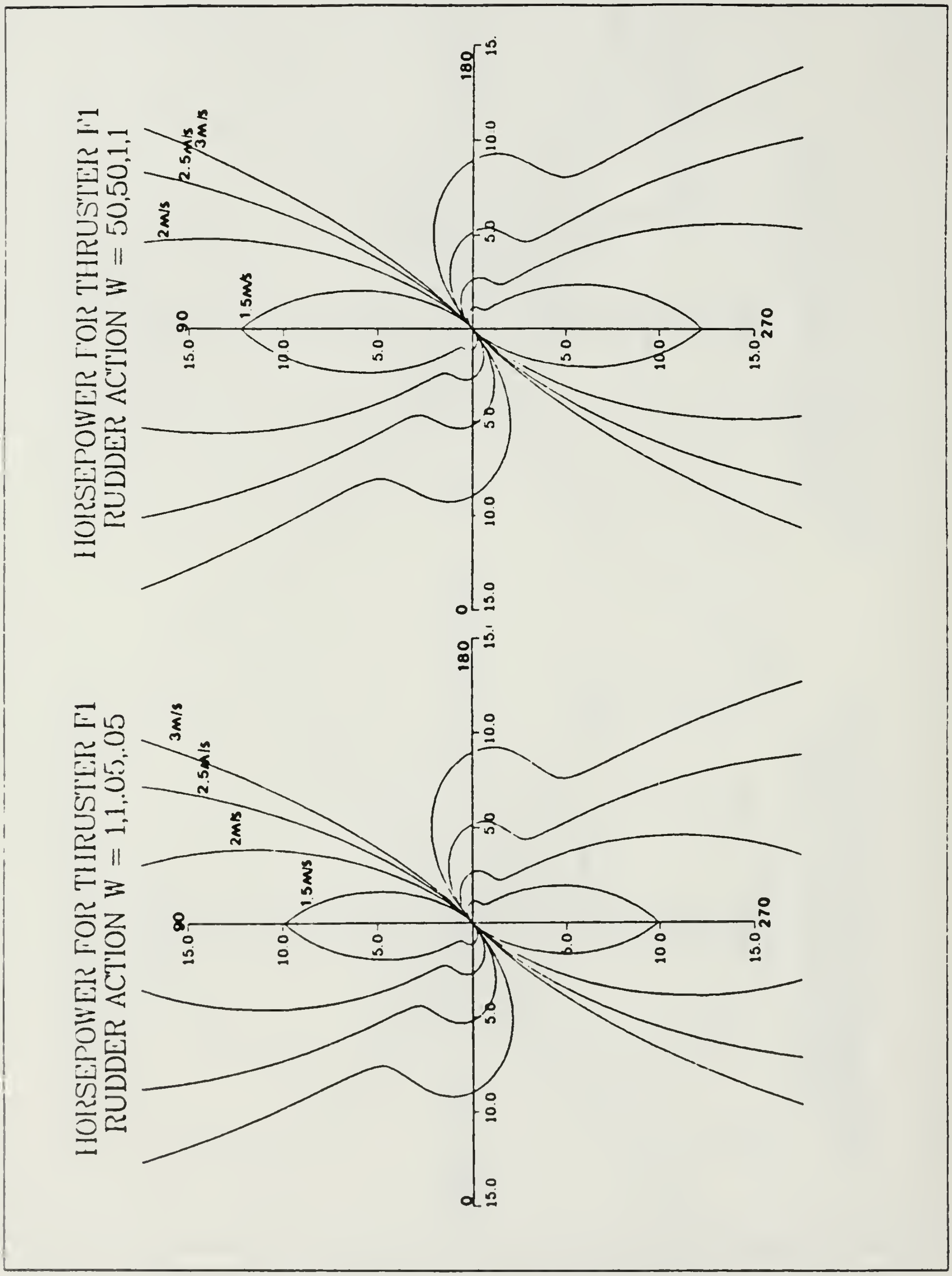

Figure 5.8 Effects of Changing Weights on F1 With Rudder Action.

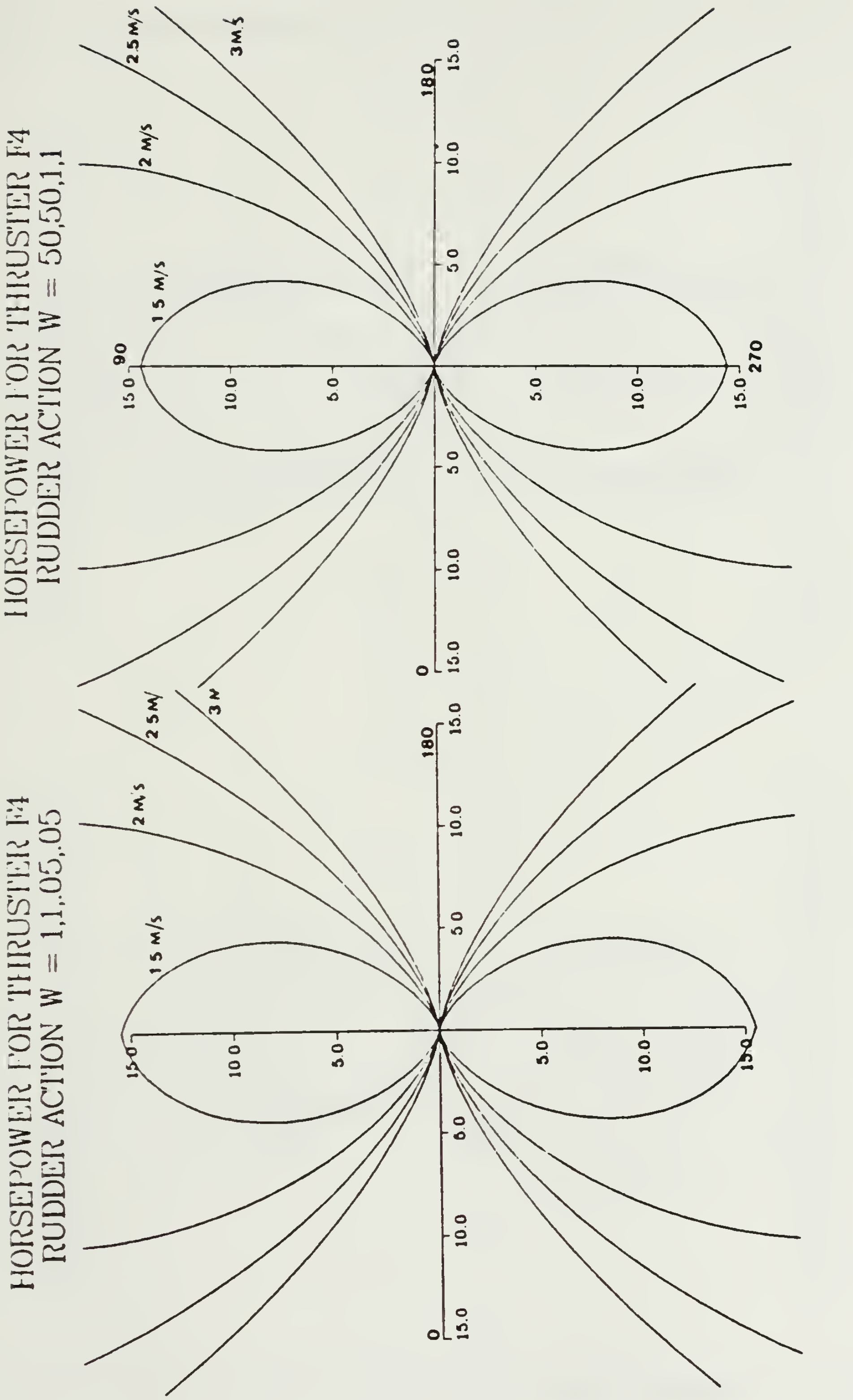

Figure 5.9 Effects of Changing Weights on F4 With Rudder Action.

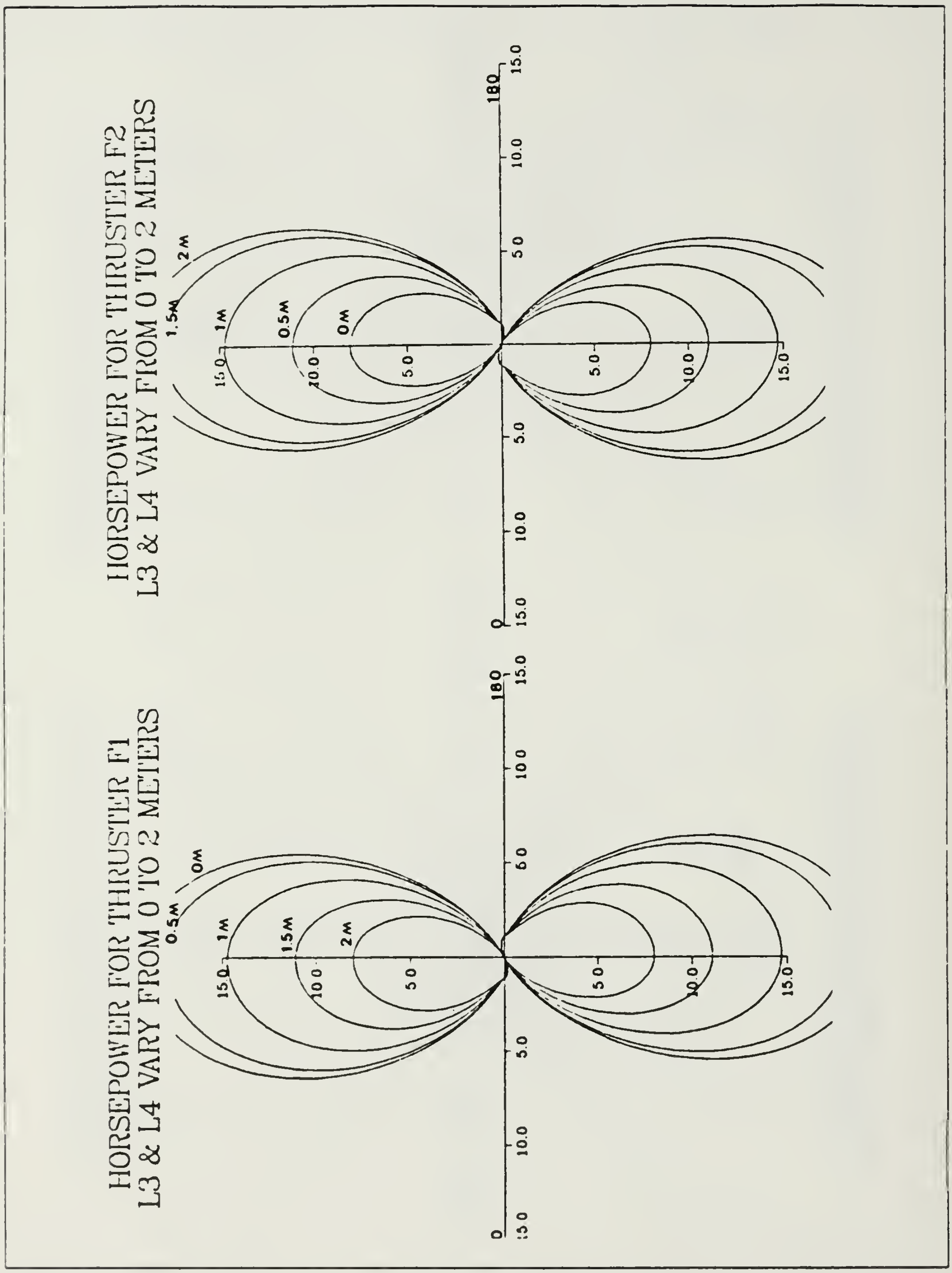

Figure 5.10 Effects of Changing The Location of Lateral Thrusters in a 1.5 M/S Current.

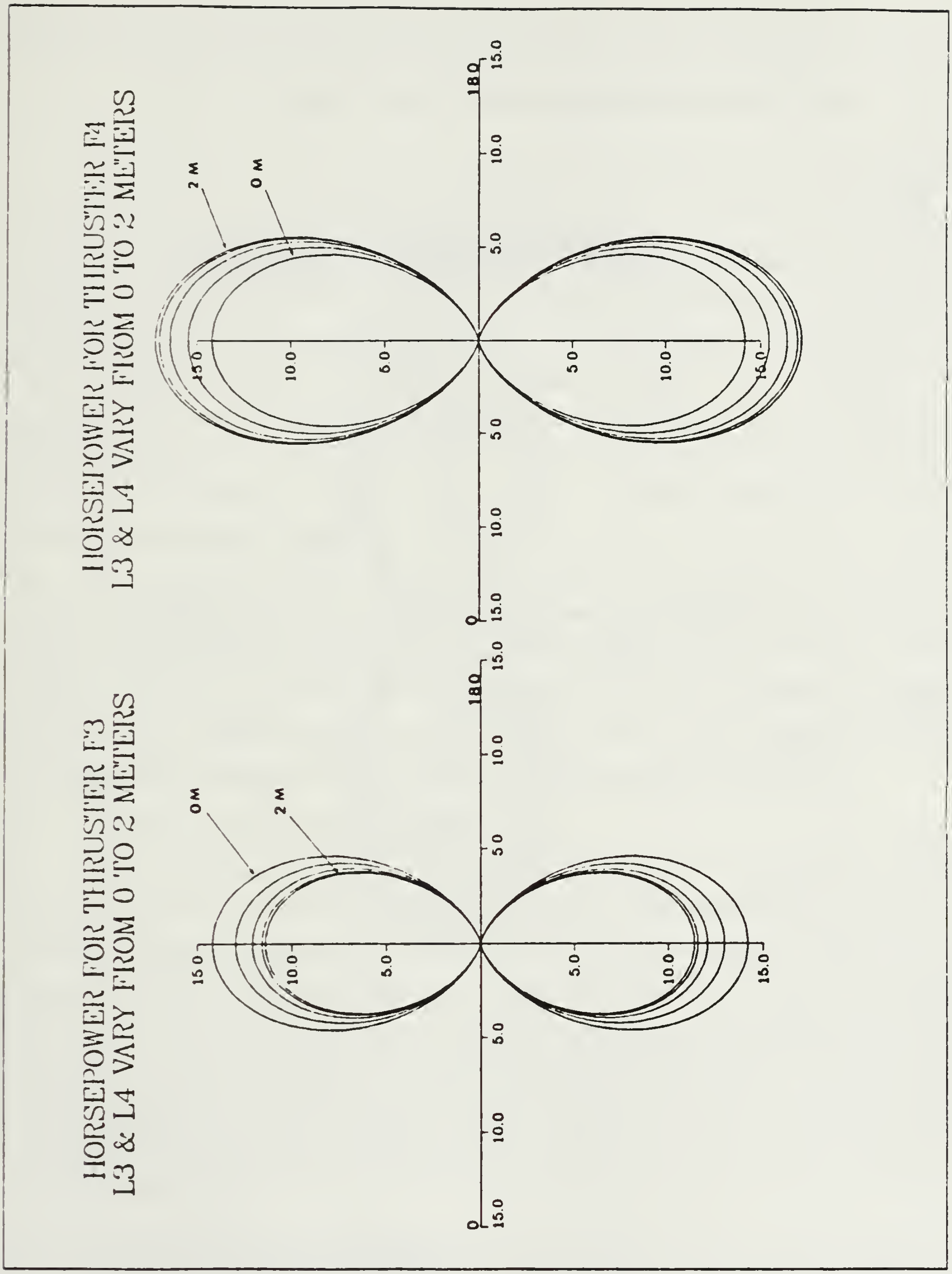

Figure 5.11 Effects of Changing The Location of Lateral Thrusters in a 1.5 M/S Current.

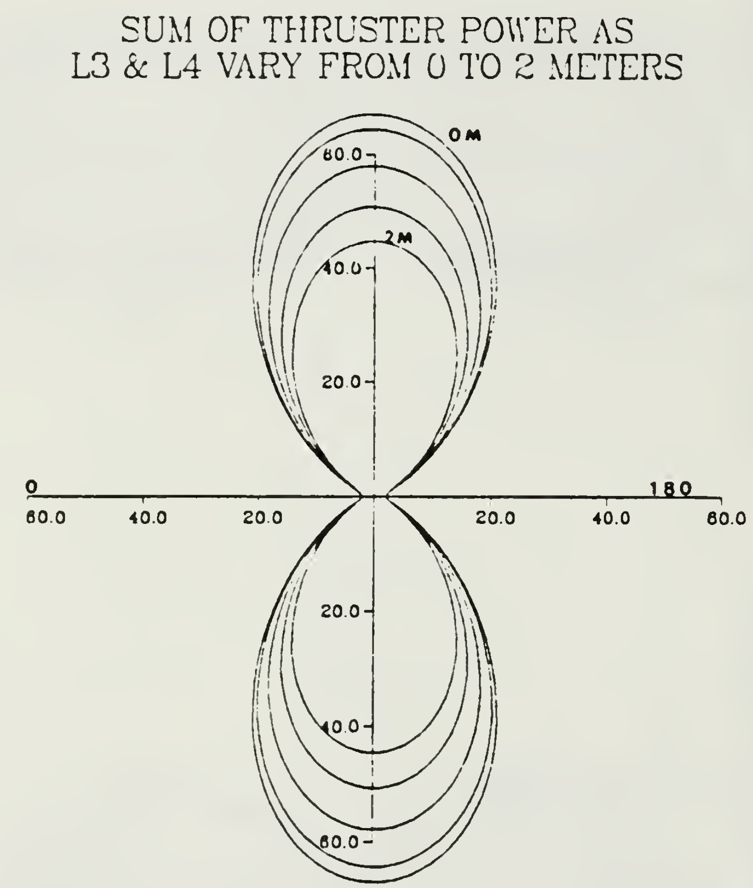

Figure 5.12 Effects on the Total Power of Varing The Lateral Thrusters Location in a 1.5 M/S Current.

VI. A CONCEPTUAL FORCED BASED CONTROLLER

AUV motion has to respond to a changing set of constraints. The dynamics of the vehicle are a function of speed, depth, pitch angle, etc. Any autonomous controller developed must take into account the numerous variables and then account for the fact that they do not remain fixed over the entire range of AUV performance. This section describes the proposed model based controller, a methodology for responding to the the changing constraints through an onboard model, which is supplied with environmental data in real time and precomputed vehicle constraints. The precomputed constraints and the environmental data are used to estimate the hydrodynamically induced forces which are then allocated to the various force producing devices (thrusters, and control surfaces).

As an example, control surfaces produce different forces for a given deflection angle depending on the local velocity across the control surface. The local velocity may not be the same as the AUV velocity because of the interaction of the current and flow about the AUV. This means that the controller must be able to generate a command to the control surface taking the variability into account. The conceptual force based controller block diagram shown in Figure 6.1 could provide this flexibility.

A. MODEL BASED CONTROLLER

The model based controller is composed of several major sections. The Command and Control section is the intelligence of the AUV. It will provide the commands for course and speed, determine the mode of the AUV either internally or from a higher level of onboard control. Additionally it is where the percomputed vehicle information is stored. The AUV Model section computes the estimated hydrodynamically induced forces on the AUV based on the inputs from the Command and Control and the Navigation/Sensors (N/S) section. The Force Allocation Logic (FAL) along with the Weighting Matrix selection distribute the necessary force commands to the thrusters and control surfaces.

B. COMMAND AND CONTROL

The Command and Control (C/C) portion of the controller receives inputs from the AUV sensors and navigation. The sensors and navigation provide the C/C the

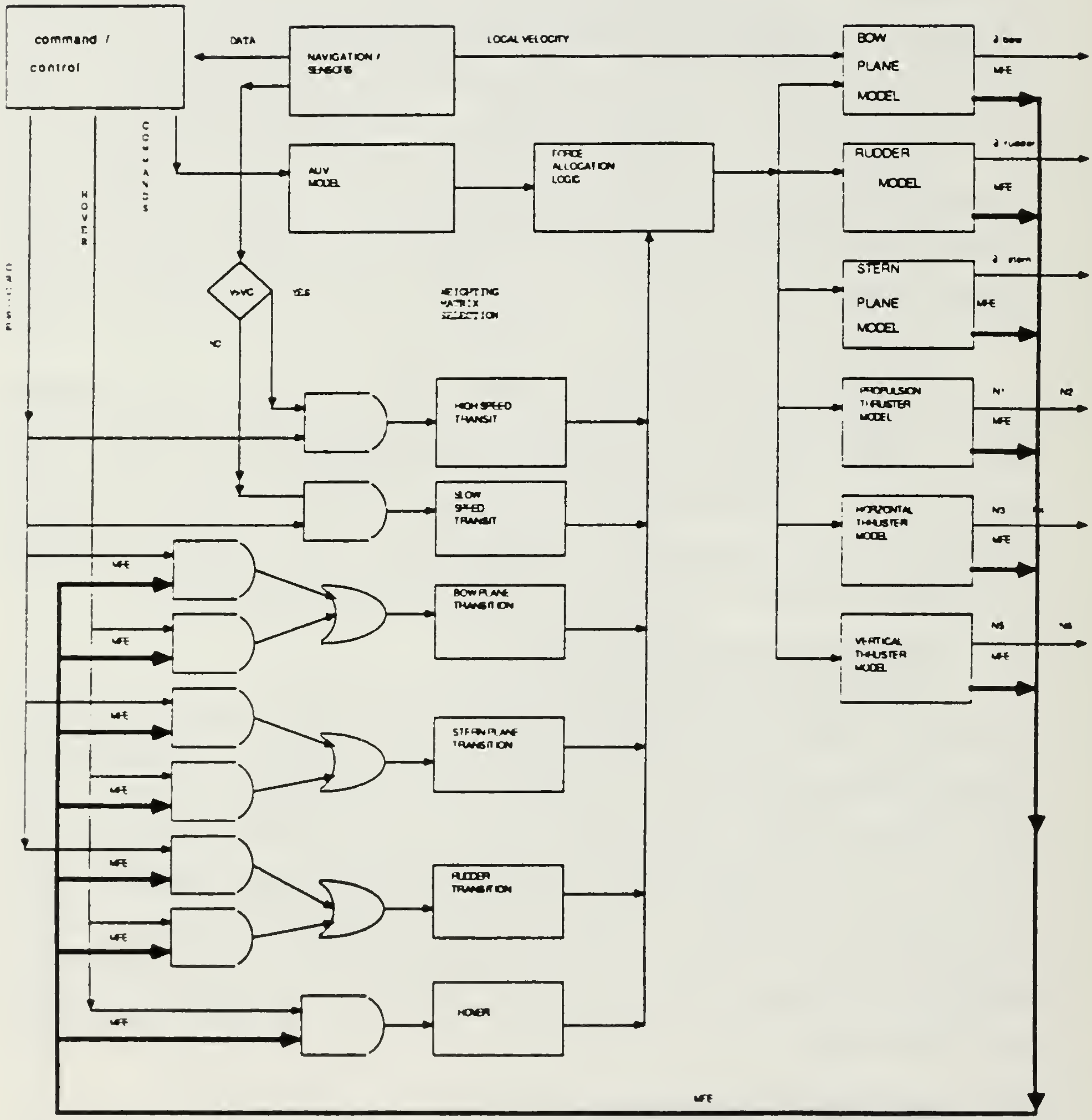

Figure 6.1 Force Based Controller.

current position, attitude, depth, and speed of the AUV. Either the C/C or some higher portion of the overall AUV control computes the desired speed, course, and allowable rates and angles (roll, pitch, and yaw). The rates and angles are based on model simulations of different maneuvers provided to the AUV prior to the mission. This does not mean the course and speed are precomputed and the AUV is following a preprogrammed path. The dynamics of the AUV have been simulated and various maneuvers evaluated to obtain the optimum rates and angles (roll, pitch, and yaw) for different types of maneuvers, and assembled into a precomputed data base. From this data base, information is provided to the AUV Model portion of the controller. Additionally the C/C provides signals to the Weighting Matrix Selection, which indicate whether the AUV is in a hovering or a transit mode.

C. AUV MODEL

The AUV model is a nonlinear model contained in the onboard software and functions in real time. A nonlinear model is considered necessary because of the cross coupling between pitch, roll, and yaw terms in the equations of motion. The straight line transit dynamics can be adequately simulated using a linear model but a linear model would not predict the high speed maneuvers adequately.

This model receives inputs from the C/C and Navigation/Sensors. The C/C provides the desired course and speed along with the vehicle constraints as described above. Additionally the current vehicle dynamics (speed, attitude, etc.) are provided by N/S. With these inputs the model would estimate the hydrodynamic forces acting on the AUV as described by Bonkal and Slotline [Ref. 12,13]. Hydrodynamic force estimates from the AUV model are then provided to the Force Allocation Logic, where the force commands for the individual thrusters and control surfaces are developed.

D. FORCE ALLOCATION LOGIC

The analysis in Chapter V is based on the use of a weighted minimum norm solution to the system of equations that describe the forces necessary to balance the hydrodynamic forces for hovering. An extension of this method is to add two additional thrusters to control vertical forces and pitch. These would be located symmetrically about L/2. For hovering the forces from the control surfaces were neglected. Once the vehicle is moving and the flow across the control surfaces is large enough these control forces can be taken into account. For an AUV that is moving, the system of equations that describe the forces acting on it will have six induced forces estimated from the AUV model;

X = Longitudinal force

Y = Lateral force

Z = Vertical force

Mz = Yaw moment

Mx = Roll moment

My = Pitch moment

The estimated hydrodynamic forces have incorporated the allowable angles and rates (pitch, roll, and yaw) for the current AUV speed and depth. Also incorporated into the estimated forces are the precomputed maneuver dynamics. Six unknown thruster forces are;

F1 = Port Longitudinal Thruster
F2 = Starboard Longitudinal Thruster
F3 = Forward Lateral Thruster
F4 = Aft Lateral Thruster
F5 = Forward Vertical Thruster
F6 = Aft Vertical Thruster

additionally four control surface forces;

F7 = Rudder Force
F8 = Stern Plane Force
F9 = Port Bow Plane Force
F10 = Starboard Bow Plane Force

These result in a system of equations which is of the same form discussed in Chapter V. Using the same technique and a 10 x 10 weighting matrix the relative weight of each control surface and thruster can be adjusted to conform to the mode of the AUV. This is accomplished by the Weighting Matrix selection logic.

E. WEIGHTING MATRIX SELECTION LOGIC

Chapter V described the use of the weighting matrix to change the relative "weight" or "worth" of the lateral thrusters. This technique can be used to change the weight of the control surfaces as the AUV changes speed or commences to hover.

At high speed, a submerged vehicle does not use the control surfaces in the same manner as it does at slower speeds as discussed by Bishop and Clayton. Control at slower speed is different than when hovering. At high speed the major control of the depth and pitch angle is accomplished with the stern plane and the bow plane motion is minimized. While at moderate and slow speed the control of pitch and depth can be primarily with the bow planes. Below a minimum speed the affect of the control surfaces (bow and stern planes) actually reverse. Dive commands cause the submarine to go up. A detailed discussion of the submarine equations of motion, the planes reversal phenomenon and the methods of depth and attitude control is discussed by Bishop and Clayton. [Ref. 14: section 8.5 & 8.6]

The details will not be discussed here. This brief discussion was to highlight the need to change the weight of the bow and stern planes in the normal operation of the AUV. When the AUV is slowing from a transit mode to a hovering condition the control surfaces may lose the ability to generate force. The control surface weights must be decreased and the thruster weights must be increased for heading control and position keeping.

The weighting matrix selection shown in Figure 6.1 uses inputs from the N/S to determine if the speed is above the critical speed to change the weight of the stern and bow planes. The speed signal is coupled with a cruise signal from the C/C to preclude the inadvertent changing of the weights.

The control surface weights are developed using hovering and cruise signals from the C/C coupled with a maximum force signal from the respective control surface model. Each control surface receives a force command input from the force allocation logic, additionally a local velocity signal is provided from sensors on each control surface. A local velocity signal for each control surface simplifies the AUV model. It removes the necessity to develop an AUV model that fully describes the flow about the AUV in all possible configurations of cross flow and vehicle speed. The cross flow and the flow across each control surface is measured directly. Placing a sensor simular to the weather vane device described in Chapter II, or a system of pitot tubes on the control surface will provide the local velocity signal. These measured flows are used to estimate the hydrodynamic forces. If a control surface is given a force command that exceeds the maximum force the surface can develop, the control surface model generates a signal to the weighting matrix selection which changes the weight of the control and the associated thrusters.

Once the AUV's speed is slow enough that the control surfaces are no longer effective the maximum force exceeded (MFE) signal together with the cruise and hover commands from the C/C shift the force from the control surface to the vertical thruster for pitch control, or the lateral thrusters for heading control. When the AUV shifts into a hovering mode the weights are gradually shifted to the thrusters as the AUV slows down and the MFE signals are received from the control surface models.

F. CONTROL SURFACE MODELS

The control surface model is used to convert the force command from the FAL into a deflection angle for the control. Also the model will generate a maximum force signal. The maximum force signal is developed by computing the maximum lift possible for the measured flow across the control surface. This maximum force is compared with the force commanded from the FAL. When the commanded force exceeds the computed maximum force the MFE signal is generated. The MFE signal is used in the weighting matrix selection to change the weights of the control surfaces and shift the force from the control surface to either a thruster or another control surface.

G. THRUSTER MODELS

The thruster models, like the control surface models, convert force commands received into commands useful to the thrusters. Instead of a deflection angle, a speed command is generated. A maximum force exceeded (MFE) signal is also necessary. But instead of using a local velocity to compute the maximum force, the maximum RPM allowed for the thruster is used. This can be the based on the limiting motor speed or an arbitrary limit determined by the mode the AUV is in currently. When the AUV is hovering the speed limit for the longitudinal thrusters would be based on the power limit. Where as the speed limit for cruising would be based on the maximum allowable RPM for the motor.

H. MODEL BASED CONTROLLER SUMMARY

The model based controller utilizes precomputed AUV dynamics from model simulations and real time environmental inputs to estimate the hydrodynamic forces acting on the AUV. The onboard AUV model provides the estimated forces to the force allocation logic, which distributes the forces to the control surface and thruster models, based on the weighting values provided. The control surface and thruster models convert the forces into deflections and speed commands. Additionally the models provide a feedback signal to the weighting matrix selection to adjust the

weights of the different control surfaces and thrusters. The navigation and sensors also provide feedback to the Command and Control of speed, position, and attitude. A feed forward signal is provided from the command and control to the weighting selection logic. The system outlined will provide the variable control of the AUV necessary to account for the changing constraints experienced over the range of AUV performance.

VII. SUMMARY AND RESULTS

This thesis has shown that an autonomous hovering system is feasible. The anslysis of the hovering problem examined the exact solution utilizing three thrusters. A redundant solution utilizing four thrusters was examined. Finally a methodology for an autonomous controller was presented.

A. SUMMARY

Three thrusters, two longitudal and two lateral, were capable of countering hydrodynamically induced forces from currents up to 1 M/S. The location of the lateral thruster was restricted to a position aft of the center of action, 1.3 meters maximum. The power required increased as the position of the lateral thruster was moved aft. This was opposite of the affect seen when four thrusters were analyzed.

The analysis of four thrusters provided redundant lateral thrusters. A unique solution to the resulting system of equations was impossible. This was overcome by using a weighted minimum norm solution, which provided added flexibility. When all the weights of the thrusters were one, the system did not perform any better than the three thruster system. But by adjusting the weights of the thrusters the power necessary to balance the hydrodynamically induced forces was shifted from the lateral thrusters to the longitudinal thrusters. The analysis also showed that the power decreased as the lateral thrusters were moved away from the center of action. The best performance was obtained when the lateral thrusters were maintained in a symetric position on either side of the center of action.

An extension of the weighted solution for the hovering problem was proposed as a basis for an autonomous controller. The controller required a nonlinear model to estimate the the hydrodynamiclly induced forces resulting from current and AUV motion. The model inputs were from the onboard navigation and sensors, plus precomputed state values. Model simulations computed the desired or required state variables for different maneuvers and these valued were stored onboard. When the command and control wanted a maneuver it provided the AUV model the desired states. Navigation and sensors provided the enviromental data. From these inputs the model estimated the hydrodynamic forces acting on the AUV. The force allocation logic then computes force commands for the thrusters and control surfaces based on

the weights received from the weighting matrix selection logic. Force commands are given to the control surface and thruster models, where they are converted into deflection angles or speed comands. Should the capabilities of one of the control surfaces or thrusters be exceeded, a maximun force exceeded command is fed back to the weighting matrix selection logic and changes the approiate weights. This allows for the smooth transition from crusing mode to hovering mode.

B. LIMITATIONS

- This study utilized idealized conditions which simplified many equations. The hovering problem was considered to be a static problem in only the X and Y planes. When in fact it is a dynamic problem with six degrees of freedom.
- The interaction of the thruster jet with the incident flow was not considered. This problem is very complex especially for currents coming from 30° on either side of the stern.
- The weighting matrix may be illconditioned. This would require a different approach to solve the redundant system of equations.

C. RECOMMENDATIONS

The following areas of additional study are recommended:

- The interaction of the thruster jet with the hull as β changes and the affects of the ability to hover or maneuver at slow speeds.
- Hull shapes best suited for a mission requiring both crusing and hovering station keeping.
- Optimum values for the weighting matrix for the different modes of the AUV.

APPENDIX
CODE USED TO DEVELOP POWER ESTIMATES

```
      REAL PI,W,L,H,RHO,FX,FY,CDX,CDY,APX,APY,U,UX,UY,D,APR,F1,F2,F3,XX
      REAL FT(210),BETA(210),ANGLE,FTT(210),N1,N2,N3,M,KT,X(3),Y(4)
      REAL FTN(210),MB, SHP1(210),SHP2(210),SHP3(210),SHP4(210)
      REAL F31(210),F32(210),F33(210),L1,L2,LIMIT(210),LIMIT1(210)
      REAL TOTAL(210)
CCC DIMENSIONS OF THE AUV
      W= 2.0
      L= 5.5
      H= 1.0
      PI= 4.*ATAN(1.)
CCC   CALCULATE THE FORCES ON THE AUV
      APX = H*W
      APY = H*L
      RHO = 998.2
      APR = 0.254
      KT = 0.45
      D =1.0/3.0
      U = 3.0
      CDX = 0.35
      CDY = 0.6
      CDR = 2.0
      L1 = 1.19
      L2 = -1.19
      BETA(1) = 0.0
C FOR OUTPUT TO FILES DISABLE THE CALL FOR ALL GRAPHICS DEVICES
C      CALL TEK618
           CALL SHERPA('T3F3NORD','A',3)
      CALL COMPLX
C FORMAT THE TABLES FOR GRAPHICS OUTPUT
C      WRITE(15,1100)
C      WRITE(16,500)
C      WRITE(16,510)
C      WRITE(16,520)
C      WRITE(17,530)
C      WRITE(18,540)
C      WRITE(20,560)
        XX = 1000.0

      DO 30 J=1,5
C FORMAT THE PAGE FOR GRAPHICS OUTPUT
C      CALL PAGE (8.5,6.)
C      CALL NOBRDR
      CALL AREA2D (6.,6.)
      CALL YAXANG(0)
      CALL XNAME(' ',1)
      CALL YNAME(' ',1)
C      CALL HEADIN ('FORCE (KN) VS SIDE SLIP ANGLE', 29 ,1.5,3)
C      CALL HEADIN ('MOMENT VS SIDE SLIP ANGLE', 25 ,1.5,3)
C      CALL HEADIN  ('HORSEPOWER FOR THRUSTER F2 VS SIDE SLIP ANGLE',45,
C    * 1.5,3)
      CALL HEADIN  ('HORSEPOWER FOR THRUSTER F3 ',27,
     * 1.5,2)
      CALL HEADIN  ('RUDDER REMOVED'            ,14,
     * 1.5,2)
C      CALL HEADIN  ('RUDDER ACTION W = 1,1,1,1',25,
C    * 1.5,2)
C     CALL HEADIN  ('SUM OF THRUSTER POWER AS', 24,
C    * 1.5,2)
C      CALL HEADIN ('L3 & L4 VARY FROM 0 TO 2 METERS',31,1.5,2)
C      CALL HEADIN ('CDX = 0.35, CDY = 0.6', 21 ,1.5,3)
C      CALL HEADIN ('CURRENTS 4 M/S TO 1 M/S', 23 ,1.5,3)
```

```
        CALL POLAR(1, 15 ,3.,3.)
CCC CALCULATE THE HYDRODYNAMIC FORCES INDUCED ON THE AUV
                DO 40 I=1,200
                UX = U * COS(BETA(I))
                UY = U * SIN(BETA(I))

                     FX = .5*CDX*RHO*APX*(UX**2)
                     FYS= .5*CDY*RHO*APY*(UY**2)
CCC DEVELOPE RUDDER POSITION
CCC IF NO RUDDER ACTION REQUIRED CHANGE FLAG TO '0'
         FLAG = 11
        IF (FLAG .EQ. 0) THEN
        FR =  0.5*CDR*RHO*APR*UY**2
        ELSE
CCC MANIPULATE THE RUDDER TO MINIMIZE THE MOMENT
        IF((BETA(I) .GE. 11.0*PI/6.) .AND. (BETA(I) .LE. 2.0*PI)) THEN
          ALPHA= BETA(I)-2.0*PI
          FR = 0.0
         ENDIF
         IF((BETA(I) .GE. 0.0) .AND. (BETA(I) .LE. PI/6.0)) THEN
           ALPHA = BETA(I)
           FR = 0.0
         ENDIF
        IF((BETA(I) .GT. PI/6.0) .AND. (BETA(I) .LE. PI/2.0)) THEN
             ALPHA = PI/6.
             FR = .5*CDR*RHO*APR*(U * COS(ALPHA+(PI/2.0)-BETA(I)))**2
         ENDIF
        IF((BETA(I) .GT. PI/2.0) .AND. (BETA(I) .LT. 5.*PI/6.0)) THEN
             ALPHA = -PI/6.
             FR = .5*CDR*RHO*APR*(U * SIN(PI-BETA(I)+ALPHA))**2
         ENDIF
         IF((BETA(I) .GE. 5.0*PI/6.0) .AND. (BETA(I) .LE. 7.*PI/6.)) THEN
             ALPHA = BETA(I)-2.0*PI
             FR = 0.0
         ENDIF
         IF((BETA(I) .GT. 7.*PI/6.) .AND. (BETA(I) .LE. 3. *PI/2.)) THEN
             ALPHA = PI/6.
             FR =.5*CDR*RHO*APR*(U*COS((3.*PI/2.)-BETA(I)+ALPHA))**2
         ENDIF
        IF((BETA(I) .GT. 3.0*PI/2.0) .AND. (BETA(I) .LT. 11.*PI/6.)) THEN
             ALPHA = -PI/6.
             FR = .5*CDR*RHO*APR*(U * SIN((2*PI)-BETA(I)+ALPHA))**2
         ENDIF
         ENDIF
           MB= SQRT((FX**2)+(FY**2))* 0.204*COS((PI/2.0)-BETA(I))
CCC DETERMINE THE SIGN OF THE FORCES
           IF((BETA(I) .GE. 0.0) .AND. (BETA(I) .LE. PI/2.0)) THEN
                     FX = -FX
                     FY = -FYS
                     FR = -FR
            ENDIF
           IF((BETA(I) .GT. PI/2.0) .AND. (BETA(I) .LE. PI)) THEN
                     FX =  FX
                     FY = -FYS
                     FR = -FR
            ENDIF
           IF((BETA(I) .GT. PI) .AND. (BETA(I) .LE. 3.*PI/2.0)) THEN
                     FX =  FX
                     FY =  FYS
            ENDIF
           IF((BETA(I) .GT. 3.*PI/2.0) .AND. (BETA(I) .LE. 2.*PI)) THEN
                     FX = -FX
                     FY =  FYS
            ENDIF
                     FY = (FY+FR)
                     MR = -3.08 * FR
C                 M = MR + MB
C THIS LINE TO BE USED WHEN RUDDER MOMENT REMOVED
```

```
                  M = MB
                  X(1) = FX
                  X(2) = FY
                  X(3) = M
C THESE EQUATIONS EVALUATE THE THRUSTER FORCES WITH F3 FOWARD OF THE
C CG
C               F1= -.5 * FX - M + 2.954 * FY
C               F2= -.5 * FX + M - 2.954 * FY
C               F3= -FY
                  F31(I)= -.5 * FX - M + L1    * FY
                  F32(I)= -.5 * FX + M - L1    * FY
                  F33(I)= -FY
C THESE EQUATIONS EVALUATE THE THRUSTER FORCES WITH F3 AFT OF THE CG
C
C                F1= -.5 * FX - M - 2.954 * FY
C                F2= -.5 * FX + M + 2.954 * FY
C                F3= -FY
                  N1 = (SQRT(ABS(F1/(KT*RHO*D**4)))*60.)
                  N2 = (SQRT(ABS(F2/(KT*RHO*D**4)))*60.)
                  N3 = (SQRT(ABS(F3/(KT*RHO*D**4)))*60.)
               FT(I) = SQRT((FX**2)+(FY**2))/XX
CC           FTT(I) = ABS(F1/XX)+ABS(F2/XX)+ABS(F3/XX)
               FTT(I) = ABS(M/XX)
               ANGLE = BETA(I)*180.0/PI
               LIMIT(I) = 15.0
               LIMIT1 (I) = 25.0
C       WRITE (17,300) N1,N2,N3,ANGLE,CDX,CDY,U*1.944
C       WRITE (18,400) FX/XX,FY/XX,FR/XX,MR/XX,MB/XX,ANGLE,
C    A  F1/XX,F2/XX,F3/XX,U*1.944
C GENERATE THE MINIMUM NORM FORCES FOR FOUR THRUSTERS
          CALL WNORM(X,Y,L1,L2)
C       CALL CWNORM(X,Y)
         FTN(I) = ABS(Y(1)/XX)+ABS(Y(2)/XX)+ABS(Y(3)/XX)+ABS(Y(4)/XX)
C       WRITE (16,200) FT(I),FTT(I),FTN(I),ANGLE,CDX,CDY,U*1.944
C       WRITE (15,1000) Y(1)/XX,Y(2)/XX,Y(3)/XX,Y(4)/XX,ANGLE,CDX,CDY
C    A  ,U*1.944
C ESTIMATE THE HORSE POWER REQUIRED FOR THE THRUSTER
C ENTER THE FORCE INTO 'T' TO ESTIMATE HP
C       RRHO = 1.9905
C       T1 = ABS(Y(1))
         T1 = ABS(F31(I))
         SHP1(I)= ((1/746.0)*(T1**1.5))/SQRT((RHO*PI*D**2)/4)
C       T2 = ABS(Y(2))
         T2 = ABS(F32(I))
         SHP2(I)= ((1/746.0)*(T2**1.5))/SQRT((RHO*PI*D**2)/4)
C        T3 = ABS(Y(3))
         T3 = ABS(F33(I))
         SHP3(I)= ((1/746.0)*(T3**1.5))/SQRT((RHO*PI*D**2)/4)
         T4 = ABS(Y(4))
         SHP4(I)= ((1/746.0)*(T4**1.5))/SQRT((RHO*PI*D**2)/4)
C       WRITE (20,550) SHP1(I),SHP2(I),SHP3(I),SHP4(I),ANGLE,U*1.944
             TOTAL(I) = SHP1(I)+SHP2(I)+SHP3(I)+SHP4(I)
                 BETA(I+1) = BETA(I)+ PI/100.0
40           CONTINUE
          CALL CURVE(BETA,SHP3,200,0)
          CALL CURVE(BETA,LIMIT  ,200,0)
C        CALL CURVE(BETA,TOTAL,200,0)
C        CALL GRID(1 ,1)
          CALL ENDGR(I)
            U = U-0.50
C         L1 = L1 + 0.50
C         L2 = L2 - 0.50
30      CONTINUE
200     FORMAT(1X,7F10.3)
300     FORMAT(1X,7F12.3)
400     FORMAT(1X,10 F12.3)
500     FORMAT(5X,'TOTAL',5X,'TOTAL',5X,'MINIMUM',3X,'ANGLE',6X,
      A 'CDX',6X,'CDY',7X,'SPEED')
510     FORMAT(5X,'DRAG',6X,'RESULTANT',2X,'NORM',35X,'(KTS)')
520     FORMAT(5X,'FORCE (KN)', 1X,'FORCE (KN)')
```

```
530    FORMAT(5X,'N1',10X,'N2',9X,'N3',9X,'ANGLE',10X,'CDX',8X,'CDY'
      A ,9X,'SPEED')
540    FORMAT(7X,'FX',9X,'FY',10X,'FR',10X,'MR',10X,'MB',8X,
      A 'ANGLE',8X,'F1',10X,'F2',10X,'F3',11X,'SPEED')
550    FORMAT(1X,F10.5,2X,F10.5,2X,F10.5,2X,F10.5,2X,F10.3,2X,F10.3)
560    FORMAT(2X,'THRUSTER HORSEPOWER')
1000   FORMAT(1X, F10.3,2X,F10.3,2X,F10.3,2X,F10.3,2X,4F10.3)
1100   FORMAT(6X,'F1(KN)',5X,'F2',10X,'F3',10X,'F4',8X,'ANGLE',7X,
      A  'CDX',7X,'CDY',7X,'SPEED')
        CALL DONEPL
       STOP
       END

        SUBROUTINE WNORM (X,Y,N3,N4)
* THIS SUBROUTINE CALCULATES THE MINIMUM NORM SOLUTION
*  Y= AT*INV A*AT *X
        REAL A(3,4),AT(4,3),C(3,3),CINV(3,3),ATCINV(4,3),Y(4),X(3)
        REAL N1,N2,N3,N4, CINT(4,3),W(4,4)
CCC LEVER ARM VALUES FOR THE THRUSTERS
        N1 =  .5
        N2 = -.5
C      N3 =  1.19
C      N4 = -1.19
        A(1,1) = 1.0
        A(1,2) = 1.0
        A(1,3) = 0.0
        A(1,4) = 0.0
        A(2,1) = 0.0
        A(2,2) = 0.0
        A(2,3) = 1.0
        A(2,4) = 1.0
        A(3,1) = N1
        A(3,2) = N2
        A(3,3) = N3
        A(3,4) = N4
C  CONSTRUCT A TRANSPOSE
        DO 1000 I=1,3
            DO 1005 J=1,4
                AT(J,I)= A(I,J)
 1005     CONTINUE
 1000  CONTINUE
C CONSTRUCT A WEIGHTING MATRIX
        DO 10 I=1,4
        DO 20 J=1,4
        W(I,J) = 0.0
20     CONTINUE
10     CONTINUE
        W(1,1) =  1.0
        W(2,2) =  1.0
        W(3,3) =  1.00
        W(4,4) =  1.00
CCC GENERATE THE MINIMUM NORM SOLUTION
C CALCULATE W*AT
        CALL VMULFF(W,AT,4,4,3,4,4,CINT,4,IER)
C CALCULATE A*W*AT
        CALL VMULFF(A,CINT,3,4,3,3,4,C,3,IER)
C CALCULATE INV A*W*AT
        CALL LINV1F(C,3,3,CINV,0,100,IER)
C CALCULATE W*AT*INV A*W*AT
        CALL VMULFF(CINT,CINV,4,3,3,4,3,ATCINV,4,IER)
C CALCULATE W*AT*INV A*W*AT *X
        CALL VMULFF(ATCINV,X ,4,3,1,4,3,Y,4,IER)
        RETURN
        END
c WHEN RUNNING THIS PROGRAM IT MUST BE COMPILED IN DOUBLE PRECISION
C TO DO THIS AT NPS USE:
```

```
C 1. FOR OUTPUT TO FILES  "FORTVS NRF AUTODBL(DBL"
C 2. GRAPHICS REQUIRE THE DISPLA EXEC TO BE MODIFIED
C LINE 101 SHOULD READ "&IF .&COMP = .YES FORTVS &FNME &(AUTODBL(DBL "
C SEE THE COMPUTER CENTER TO GET THE DISPLA EXEC INTO YOUR FLIST
```

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Thesis
T4285 Thompson
c.1 A conceptual design study of a hovering system controller for an Autonomous Underwater Vehicle.